Debris/Ice/TPS Assessment and Integrated Photographic Analysis Of Shuttle Mission STS-100

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Technical Memorandum - 2004 - 211525

August, 2004

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April 19, 2001

Contributions By:

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FOREWORD

The Debris Team has developed and implemented measures to control damage from debris in the Shuttle operational environment and to make the control measures a part of routine launch flows. These measures include engineering surveillance during vehicle processing and closeout operations, facility and flight hardware inspections before and after launch, and photographic analysis of mission events.

Photographic analyses of mission imagery from launch, on-orbit, and landing provide significant data in verifying proper operation of systems and evaluating anomalies. In addition to the Kennedy Space Center Photo/Video Analysis, reports from Johnson Space Center and Marshall Space Flight Center are also included in this document to provide an integrated assessment of the mission.

Photo 1: Launch of Shuttle Mission STS-100

1.0 SUMMARY OF SIGNIFICANT EVENTS

STS-100 consisted of OV-105 Endeavor (16th flight), ET-108, and BI-107 SRB's on MLP-3 and Pad 39A. Endeavor was launched at 06:40:42 UTC (2:40:42 p.m. local) on 19 April 2001. Landing was at 12:10:42 p.m. local/eastern time on 1 May 2001.

A pulsing motion was observed from cameras E-17 and E-18 on the left and right hand OMS pods during post-launch film review. This Out-of-Family condition resulted in vehicle inspections post landing.

Post landing inspection of Orbiter tiles showed a total of 92 hits, of which 13 had a major dimension of 1-inch or larger. The Orbiter lower surface sustained 42 total hits, of which 4 had a major dimension of 1-inch or larger. The majority of the lower surface damage sites occurred on the right-hand wing glove. No unusual tile damage, or evidence of tile movement, as seen on launch films E-17 and –18, was observed on the OMS pods.

In summary, both the total number of Orbiter TPS debris hits and the number of hits 1-inch or larger were somewhat less than the family average. ET TPS venting modifications continue to have a reducing effect on the quantity and size of the damage sites

2.0 PRE-LAUNCH BRIEFING

The Debris/Ice/TPS and Photographic Analysis Team briefing for launch activities was conducted at 0800 on 19 April 2001. The following personnel participated in various team activities, assisted in the collection and evaluation of data, and contributed to reports contained in this document.

A.Oliu	NASA - KSC	Shuttle Ice/Debris Systems
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D. Leggett	Boeing	Systems Integration
B. Atkinson	Boeing	Systems Integration
T. Wilson	Boeing	Systems Integration
S. Otto	LMMSS	ET Processing
J. Ramirez	LMMSS	ET Processing
A. Khodaoust	Boeing	Shuttle Aerodynamics
M. Eastwood	Thiokol-LSS	SRM Processing

3.0 LAUNCH

3.1 PRE-LAUNCH SSV/PAD DEBRIS INSPECTION

A pre-launch debris inspection of the launch pad and Shuttle vehicle was performed on 18 April 2001. The walkdown of Pad 39A and MLP-1 included the flight elements OV-105 Endeavour (16th flight), ET-108, and BI-107 SRB's. There were no significant SSV discrepancies. Four facility items were documented in Appendix K of S0007VL4:

- Retainer pin on East egress flip platform on MLP 0-level missing a securing cotter pin.
- Both securing pins on the Southwest egress platform on MLP 0-level were missing the retainer feature.
- Three loose caps found on feed-through pipes adjacent to SSME and SRB exhaust holes at the MLP 0-level.
- Metal debris/slag found in web of horizontal beam FSS 255-foot level at Southeast corner.

All facility items were in work by Pad crew at the conclusion of the debris inspection for resolution prior to cryoload.

3.2 FINAL INSPECTION

The Final Inspection of the cryoloaded vehicle was performed on 19 April 2001 from 0830 to 1030 hours during the two-hour built-in-hold at T-3 hours in the countdown. There were no Launch Commit Criteria (LCC) or OMRS criteria violations. There was no acreage icing concerns. There was also no protuberance icing conditions outside of the established database.

A portable Shuttle Thermal Imager (STI) infrared scanning radiometer was utilized to obtain vehicle surface temperature measurements for an overall thermal assessment of the vehicle, particularly those areas not visible from remote fixed scanners, and to scan for unusual temperature gradients.

3.2.1 ORBITER

No Orbiter tile or RCC panel anomalies were observed. The RCS thruster paper covers were intact without any visible discoloration. Ice/frost had formed on the SSME #1 and #2 heat shield-to-nozzle interfaces.

3.2.2 SOLID ROCKET BOOSTERS

SRB case temperatures measured by the STI radiometers were close to ambient temperatures, 58 degrees F. All measured temperatures were above the minimum requirement.

3.2.3 EXTERNAL TANK

The ice/frost prediction computer program 'SURFICE' was run as a comparison to infrared scanner point measurements. The program predicted temperatures above the 32 degrees F throughout ET cryoload. The following table shows ambient condition, SURFICE prediction and IR surface temperatures at the start of FIT walkdown.

Ambient conditions – 0830hrs	SURFICE Predictions	IR Surface Readings
58 Degrees F.	LO2 ogive 45 Degrees F	LO2 Tank 39-56 Degrees F
64% RH	LO2 barrel 38 Degrees F	
9 knots	LH2 upper 34 Degrees F	LH2 Tank 45-56 Degrees F
306 degrees	LH2 lower 44 Degrees F	

The Final Inspection Team observed no condensation on the LO2 tank acreage with a small patch of frost on the barrel section (-Y/-Z side). The frost melted away before the inspection was completed. There were no TPS anomalies.

No significant anomalies were present in the intertank TPS. A total of seven cracks in the intertank stringer valley TPS were observed (-Y/-Z side and –Y/+Z side). None of the cracks exhibited ice, frost, nor offset. Therefore, the cracks were acceptable for flight per the NSTS-08303 criteria. Ice and frost accumulations on the GUCP were typical.

The LH2 tank was dry with no significant anomalies. Frost was observed on the aft side bondline of the –Y bipod ramp. The frost had dissipated by the end of the inspection. There was a small frost spot on the aft side of the –Y vertical strut to tank interface. There was also a small frost spot on the aft side of the +Y vertical strut to tank interface. Both frost spots on the aft side of the vertical struts were dissipating as the inspection went on. There were no acreage TPS anomalies.

Typical amounts of ice/frost had accumulated in the LO2 feedline bellows and support brackets.

A 4-inch in length and .25 inch wide stress relief crack was observed in the –Y vertical strut TPS with no offset. This condition has been observed on previous vehicles and found acceptable for flight per the NSTS-08303 criteria.

There were no TPS anomalies on the LO2 ET/ORB umbilical. Ice and frost in the LH2 recirculation line bellows and on both burst disks was typical. Likewise, a typical amount of ice/frost had accumulated on the LH2 ET/ORB umbilical purge barrier outboard side, forward, and aft surfaces. Typical ice/frost fingers were present on the pyro canister and plate gap purge vents. No unusual vapors or cryogenic drips had appeared during tanking, stable replenish, and launch.

3.2.4 FACILITY

All SRB sound suppression water troughs were filled and properly configured for launch. No leaks were observed on the GUCP or the LO2 and LH2 Orbiter T-0 umbilicals.

3.3 T-3 HOURS TO LAUNCH

After completion of the Final Inspection on the pad, surveillance continued from the Launch Control Center. Twenty-two remote-controlled television cameras and two infrared radiometers were utilized to perform scans of the vehicle. All frost formation on the acreage TPS had dissipated by T-0. At T-0 there were no OMRS or LCC violations related to ice conditions. At T-2:30, the GOX vent seals were deflated and the GOX vent hood lifted. Although frost covered some of the ET nose cone louvers - an expected condition - no ice was detected. When the heated purge was removed by retraction of the GOX vent hood, frost continued to form on the louvers until liftoff. At the time of launch, there were no ice accumulations in the "no ice zone".

STS-100 was launched at 06:40:42 UTC (2:40:42 p.m. local) on 19 April 2001.

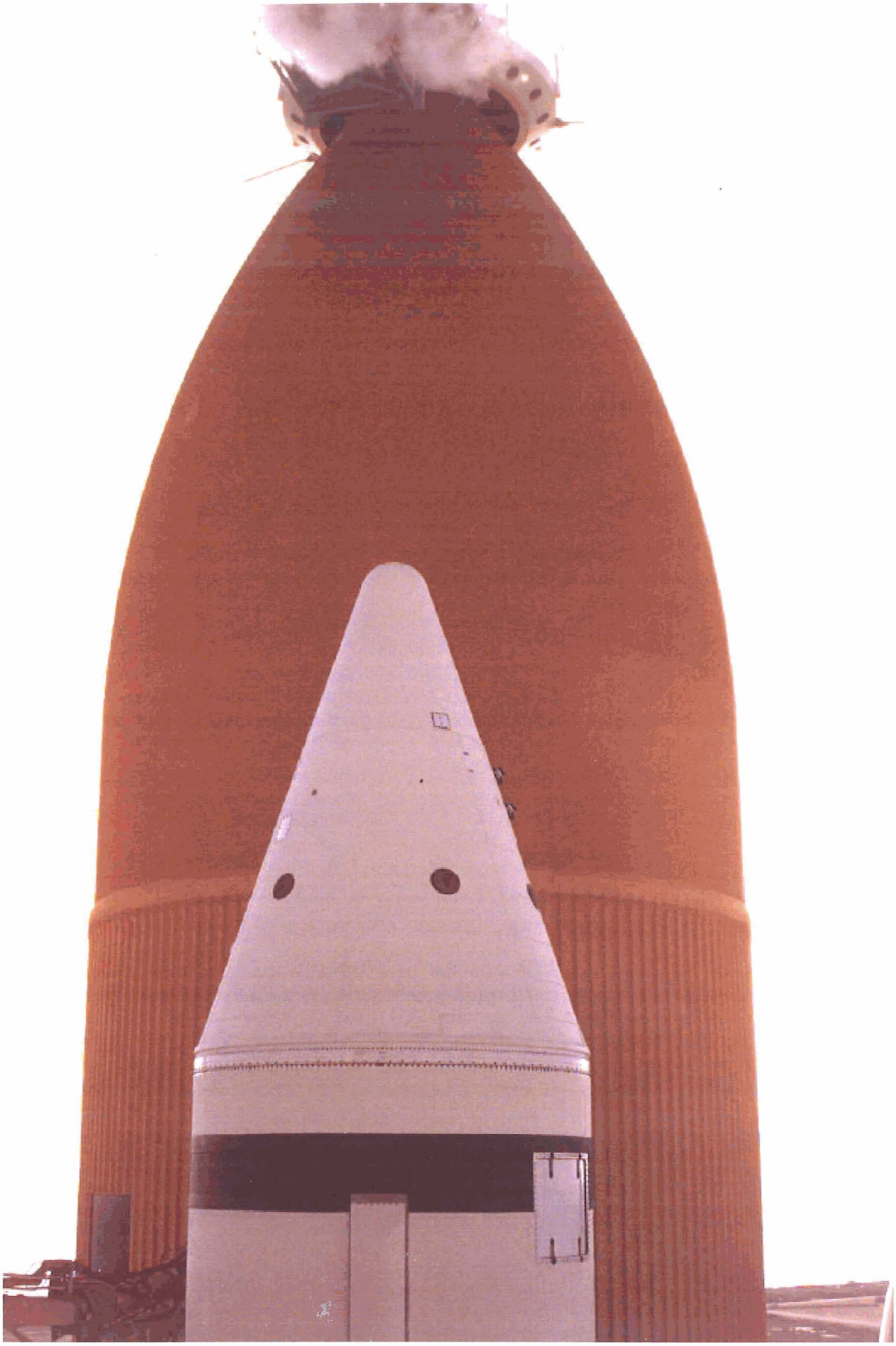


Photo 2: LO2 tank acreage.

No condensate was present on the LO2 tank acreage. Surface temperature ranged from 39 to 56 degrees Fahrenheit. There were no acreage TPS anomalies.

Photo 3: LH2 tank acreage.

No condensate was present on the LH2 tank acreage. Surface temperature ranged 45 to 56 degrees Fahrenheit. There were no acreage TPS anomalies.

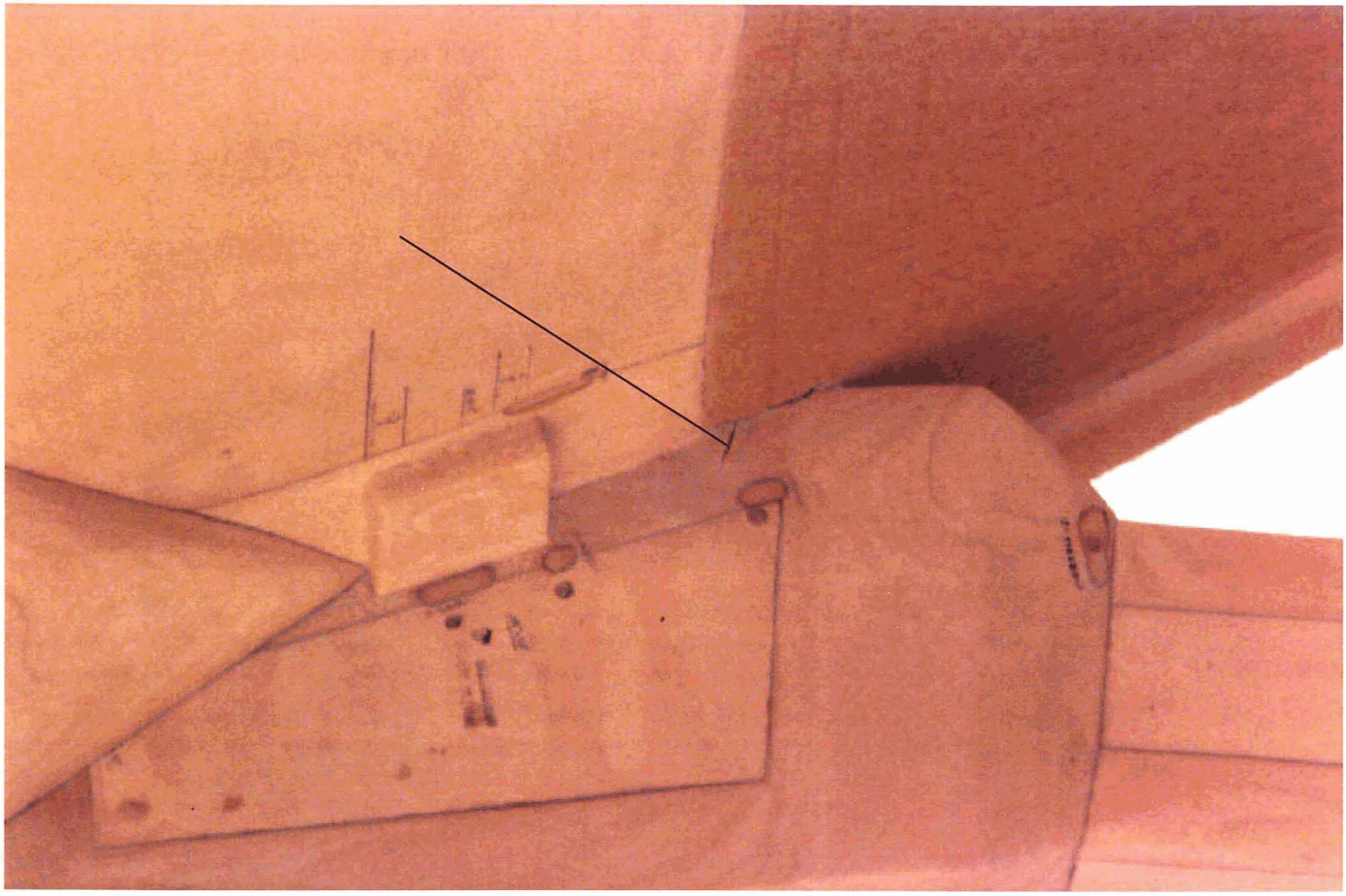


Photo 4: Crack in –Y Vertical Strut TPS

A 4 inch long and 0.25 inch wide stress relief crack was observed in the –Y vertical strut TPS with no offset. This condition has been observed on previous vehicles and found acceptable for flight per the NSTS-08303 criteria.

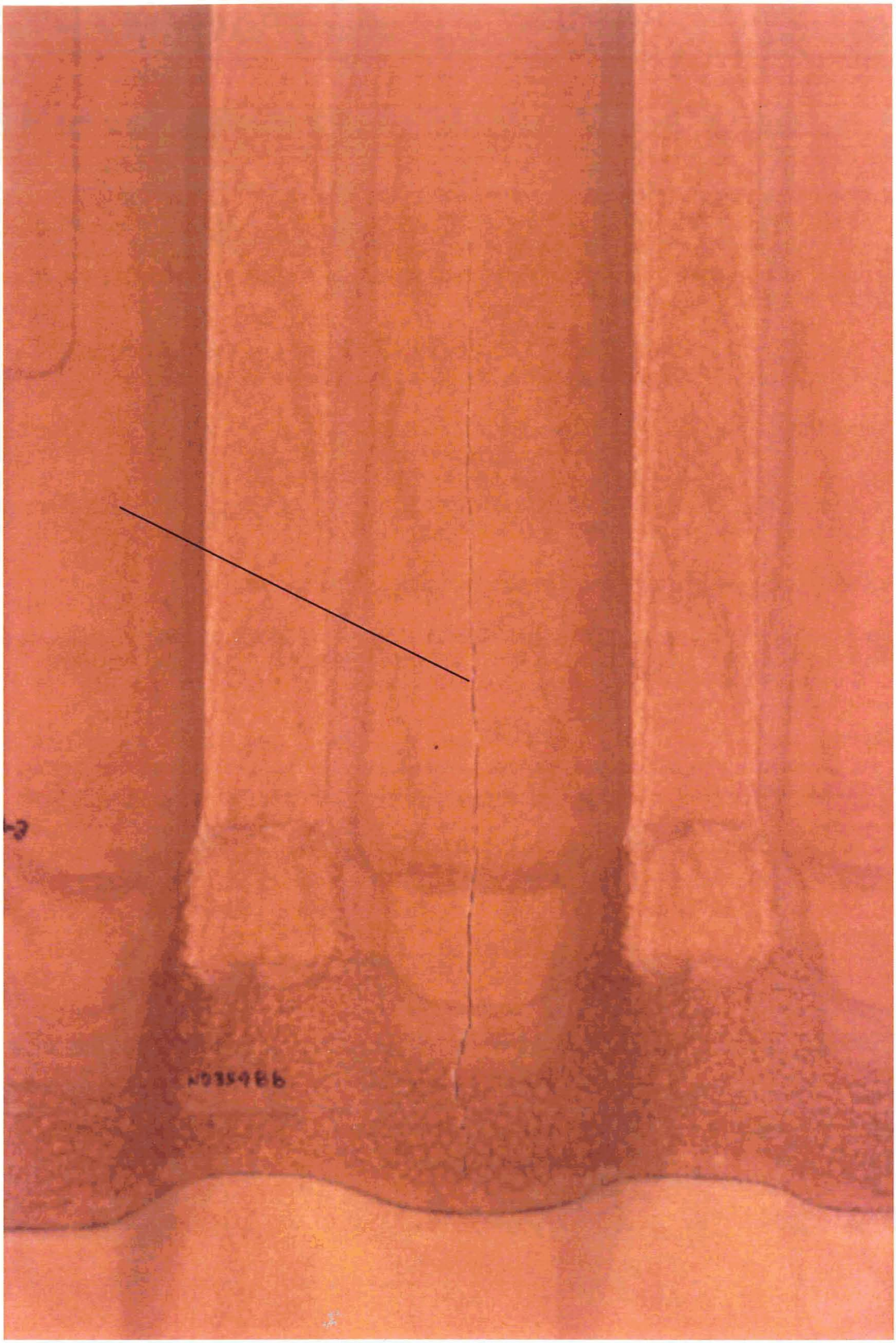


Photo 5: Cracks in Intertank Stringer Valleys

No significant anomalies were present in the intertank TPS. Seven stringer valley TPS cracks were observed (-Y/-Z side and –Y/+Z side).

4.0 POST LAUNCH PAD DEBRIS INSPECTION

The post launch inspection of the MLP-1, Pad A FSS and RSS was conducted on 19 April 2001 from Launch + 2 to 5 hours (1630 to 1915 EST). No flight hardware was found.

Orbiter liftoff lateral acceleration data to predict stud hang-ups received from Boeing-Huntington Beach indicated that no SRB holddown stud hang-up had occurred. Erosion was typical for the north posts. North holddown post blast covers and T-0 umbilicals exhibited typical exhaust plume damage. Both SRB aft skirt GN2 purge lines were intact, protective tape layering was partially eroded, but braids were not exposed.

The LO2 and LH2 Tail Service Masts (TSM) appeared undamaged and the LO2/LH2 bonnets were observed to have closed properly. The MLP deck was in generally good shape.

The GH2 vent line latched in the eighth of eight teeth of the latching mechanism. The deceleration cable failed to catch the spool weldment, no damage was noted (IPR PAD A-21771). Subsequent troubleshooting could not determine a root cause of the anomaly and the IPR was closed as an unexplained anomaly. The GUCP 7-inch QD sealing surface exhibited no damage. A detached metal ID ("dog tag") was found around the GUCP purge QD's.

The OAA appeared to be intact with no evidence of plume impingement.

All slidewire baskets were secured in place. Basket # 3 had a missing caution sign that was found nearby on the 195 ft. level. Baskets # 5, 6 and 7 had damaged/missing guard rail bumpers.

The GOX vent arm, hood, ducts and structure appeared to be in good shape with no indications of plume damage.

Debris findings included:

- 4' x 1' section of deck grating lifted out of position on FSS 115 ft-level, east side.
- A piece(12 inches long) of rusted unistrut was found on FSS 155 ft-level.
- A broken ½ inch diameter bolt (1 inch long) was found at the pad surface near the elevator landing area.

The three grass fire areas east of the pad were inspected and no flight/facility debris was found.

Overall, damage to the pad appeared to be minimal. Minimal debris was noted on pad apron and FSS.

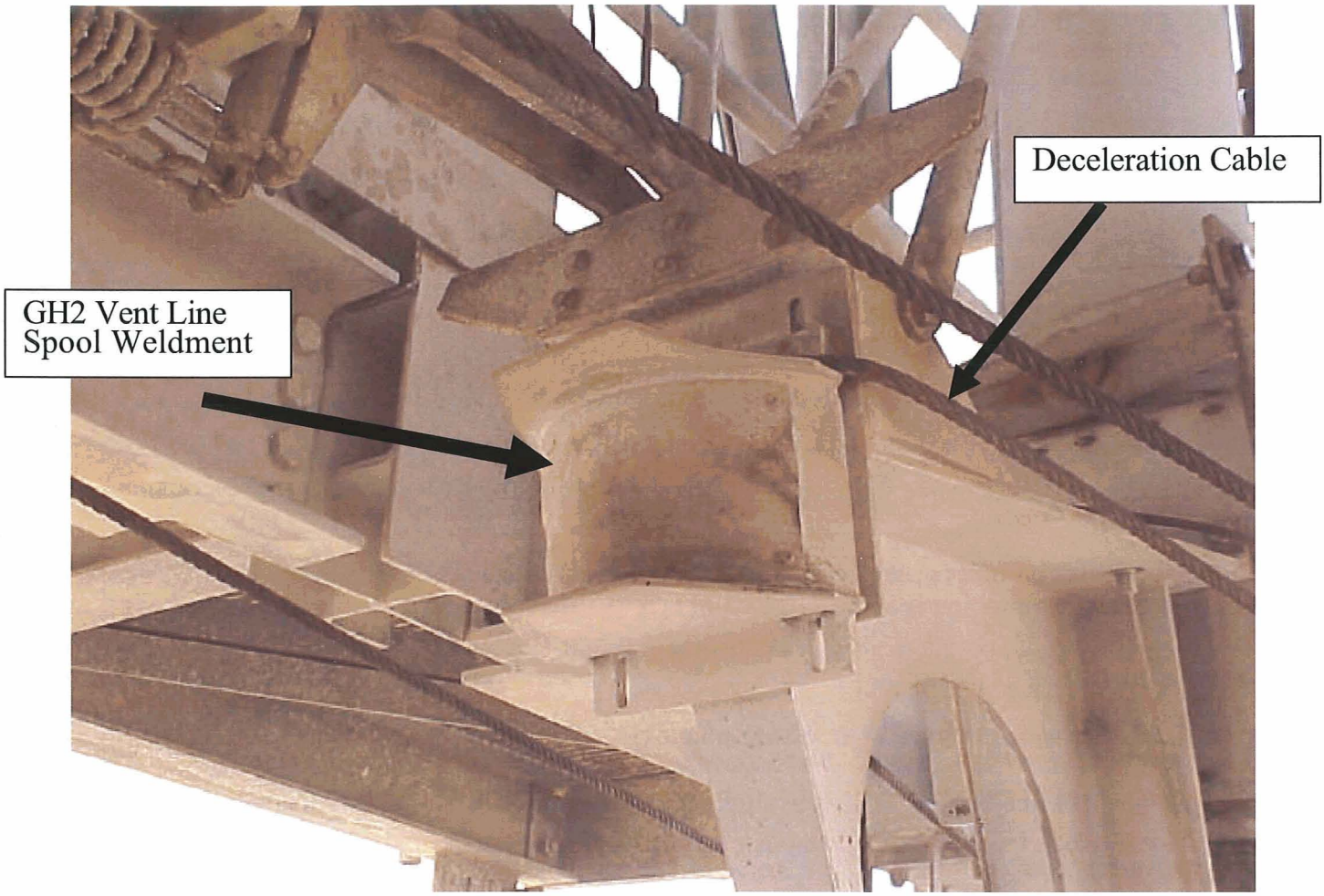


Photo 6: GH2 Vent Line Latch-back

Deceleration cable failed to catch the spool weldment, no damage was noted.

5.0 FILM REVIEW

The only anomalous condition observed during the Film Review was the apparent motion of the lower Left Hand OMS Pod TPS. MLP camera, E-18 captured the motion during SSME startup. The event begins at 109:18:40:38.386 UTC and seems to last for approximately 0.5-second. A similar motion, but substantially less in magnitude can be observed on the RH OMS Pod TPS. This event was reported to the Mission Management Team, Shuttle managers, vehicle systems engineers, and to Program Integration.

5.1 LAUNCH FILM AND VIDEO SUMMARY

A total of 61 films and videos, which included 16mm films, 35mm films, and Operational Television Video (OTV) camera videos, were reviewed starting on launch day.

Free burning hydrogen was visible near the orbiter base heat shield and base of vertical stabilizer. (OTV 070, 071, TV 7, 21).

Numerous pieces of ice from the ET/ORB umbilical shook loose and contacted umbilical sill tiles, but no damage was detected (OTV 009, 063, 054).

Nominal elevon movement was observed at SSME ignition.

LH2 and LO2 T-0 umbilical disconnect was normal (OTV 049, 050).

Small pieces of ice dislodged from ice/frost ball on aft side of the ET +Y vertical strut closeout (OTV 054).

Several ice/frost particles observed falling aft from forward LOX feedline bellows. No evidence of contact with Orbiter lower surface (OTV 061).

Four particles observed falling aft under the left hand wing. No evidence of contact with the Orbiter lower surface (OTV 009).

Streaks/flashes were observed in the SSME plume (E-207, E-220, E-222).

Small amount of free-burning GH2 was observed rising towards base of the vertical tail.

Numerous pieces of SRB throat plug material and water trough baggie material ejected from the SRB exhaust hole; none were observed to contact the Orbiter lower surface (E-54, E-76, E-77).

Body flap and elevon movement during ascent were typical (E-207, E-212, E-220).

Base heat shield movement during SSME ignition was typical (E-76, E-77).

Ice particles fell from ET/ORB umbilicals after lift-off. No impact to orbiter lower surface was noted (E-76, E-77).

SRB separation appeared normal (E-207, E-212).

Charring on the ET aft dome was typical.

Forward RCS paper covers were observed falling aft over left hand and right hand wing upper surface during early ascent.

5.2 OMS POD MOTION INVESTIGATION

Due to what appears to be flexing of the TPS on the LH OMS Pod (LP04) on STS-100 we have gone back and reviewed films E-17 and E-18 on the previous 20 launches to determine if any movement was present in those launches. The 20 previous launches gave a wide variety of launch times and lighting conditions. The results are as follows:

Of the 40 launch films reviewed (2 cameras per launch), 6 of them gave no data:

- Both sides on STS-89 due to under exposure.
- LH side (E-18) on STS-90 due to moisture on lens and underexposure.
- Both sides on STS-99 due to sunshine glare on lenses.
- RH side (E-17) on STS-97 due to excessive camera shake.

Movement was noted on two previous launches:

- Slight movement noticed on both the LH (LP05) and RH (RH05) OMS pod on STS-94.

- Slight movement noticed on the LH (LP03) OMS pod on STS-98.

Movement was also seen on the RH OMS Pod (RP01) on STS-100.

The movements noticed on STS-94, STS-98, and the RH OMS Pod on STS-100 were of significantly less magnitude than that of the LH OMS Pod on STS-100.

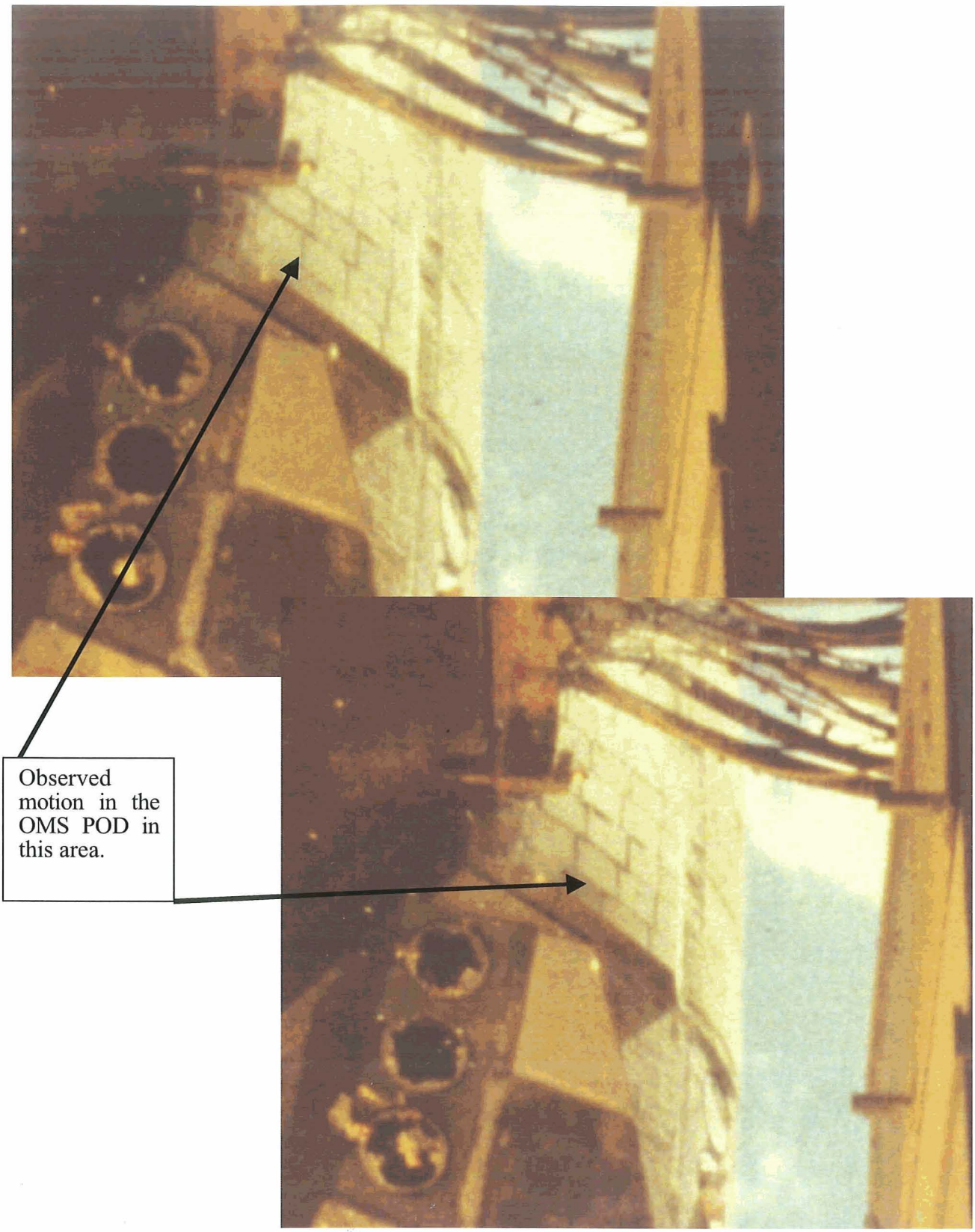


Photo 7: LH OMS Pod TPS Motion

Apparent motion observed on lower LH OMS Pod TPS surface.

5.2 ON-ORBIT FILM AND VIDEO SUMMARY

16mm film motion picture film from the LH2 umbilical cameras, as well as the 35mm still images from the LO2 ET/ORB umbilical camera and Crew Hand-Held Still Images, of the External Tank after separation from the Orbiter were received and reviewed at KSC on 11 May 2001. All images were in clear focus.

Three divots were detected on the LH2 to Intertank Flange closeout. Two of them (4-inch and 10-inch diameter) were located between the bipod struts, on the upper portion of the closeout. The third divot (6-8 inch diameter) was located in the –Y/+Z quadrant.

An additional divot (4-inch diameter) can be seen just aft of the –Y bipod ramp in the LH2 tank acreage.

The EO-2 and EO-3 separation bolt protrusion was noted.

No damage was detected on the LO2 ET/ORB umbilical disconnect, sealing surfaces, or closeout TPS. Typical ablation and divoting was noted on the vertical portion of the umbilical cable tray.

Some small, irregular, white or light-colored objects floating in field of view are believed to be pieces of frozen oxygen or hydrogen.

No anomalies were detected in the LO2 tank acreage. The BSM burn scars were typical.

Normal amounts of TPS erosion and topcoat charring occurred on the forward ogive near the nose cone, but no divots or grooves in the TPS were observed.

ET LH2 tank and intertank acreage appeared nominal.

The ablation/erosion of LO2 feedline flange closeouts was typical.

5.3 LANDING FILM AND VIDEO SUMMARY

A total of 17 films and videos, which included eight 35mm large format films and nine videos, were reviewed.

The landing gear extended properly. The right MLG tires contacted the runway first.
Drag chute deployment appeared normal. No anomalies were detected from touchdown through rollout. No unusual tile damage was visible in the films.

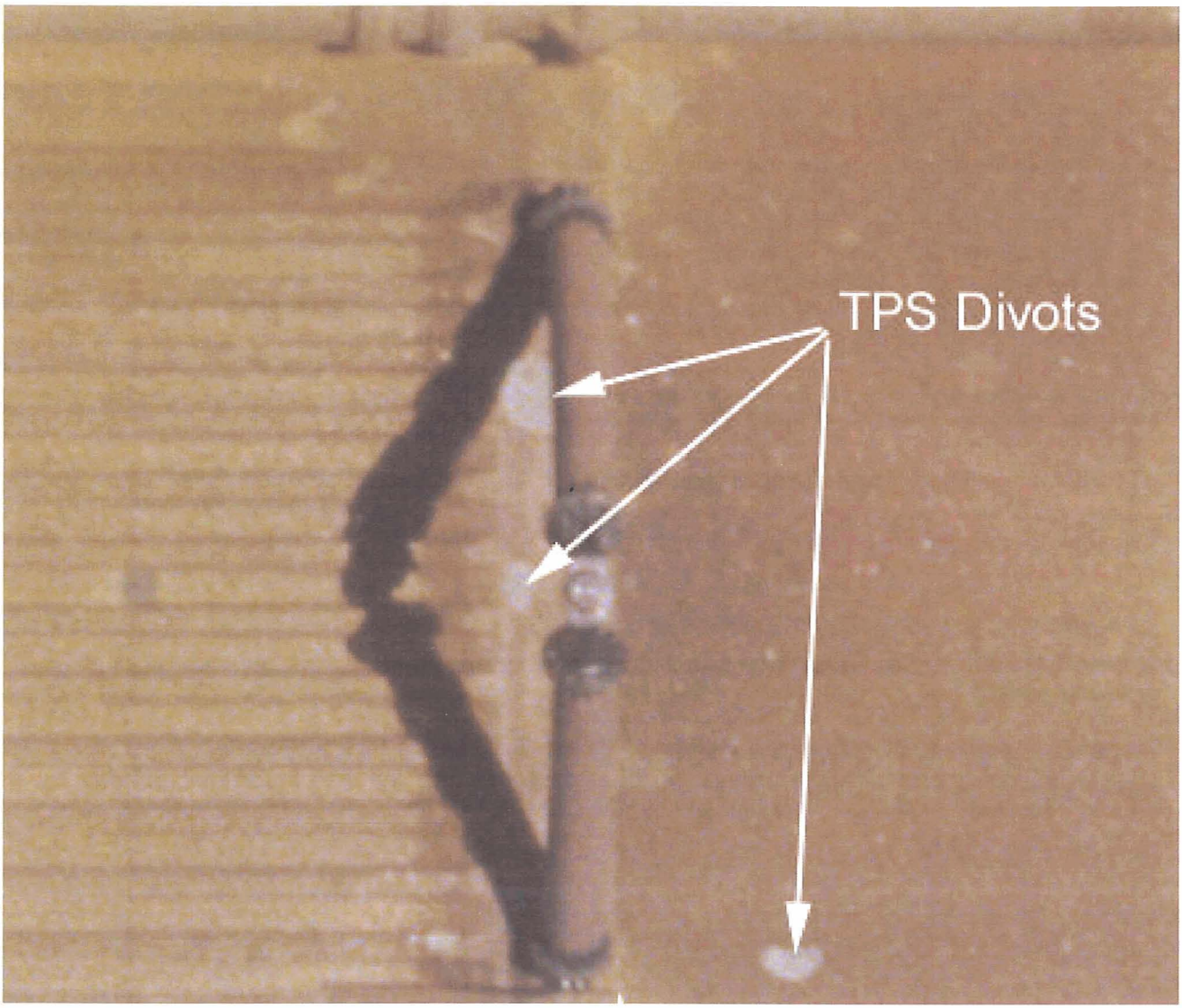


Photo 8: ET on Orbit

TPS divots observed on ET TPS

6.0 SRB POST FLIGHT/RETRIEVAL DEBRIS ASSESSMENT

The BI-107 Solid Rocket Boosters were inspected for debris damage and debris sources at CCAFS Hangar AF on 23 April 2001. Both boosters were in excellent condition.

The TPS on both frustums exhibited no debonds/unbonds. There was minor localized blistering of the Hypalon paint.

All eight BSM aero heat shield covers had fully opened and locked.

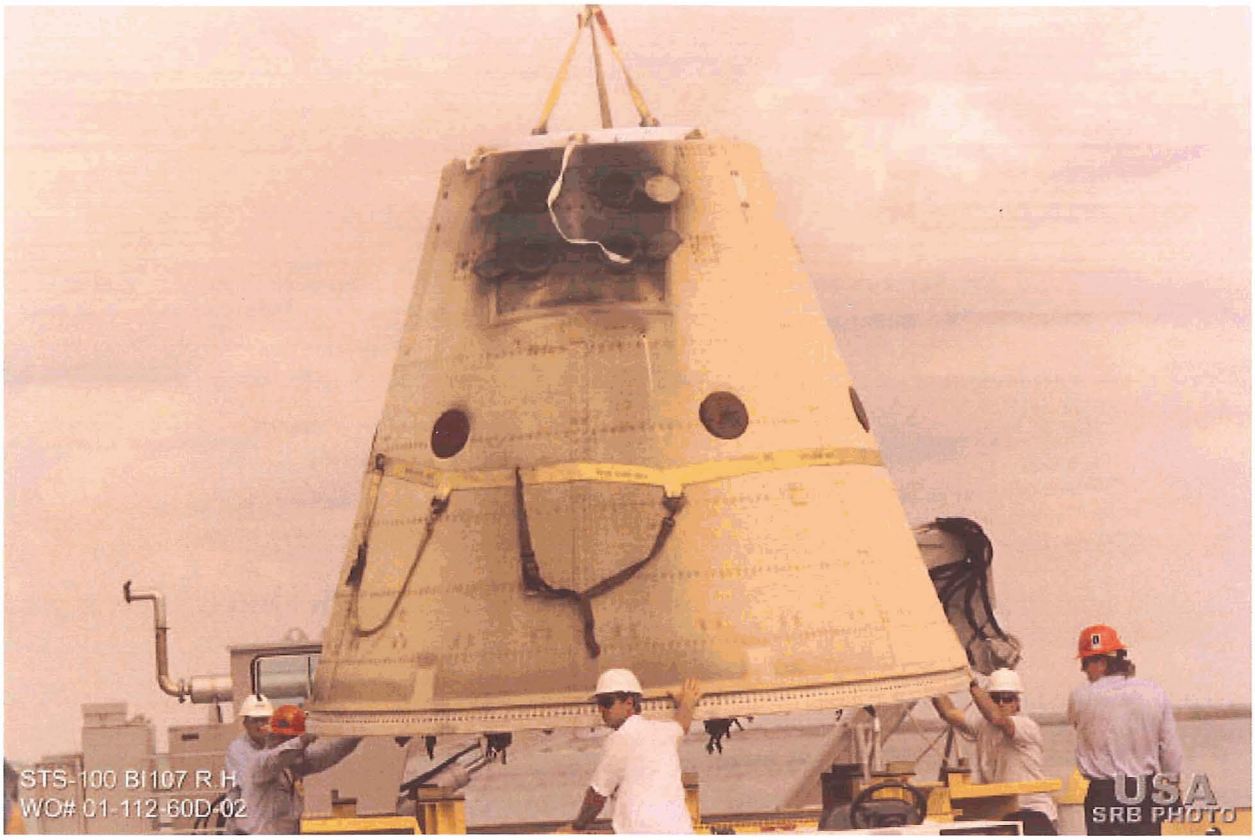
The forward skirts exhibited no debonds or missing TPS. RSS antennae were intact.

The Field Joint Protection System (FJPS) and the System Tunnel Covers closeouts were in good condition with no unbonds observed.

Separation of the aft ET/SRB struts appeared normal.

Aft skirt external surface TPS was in good condition. Typical blistering of Hypalon paint had occurred on the BTA insulation close-outs and GEI cork runs.

The holddown post Debris Containment Systems (DCS) appeared to have functioned normally. No indication of stud hang up was observed.



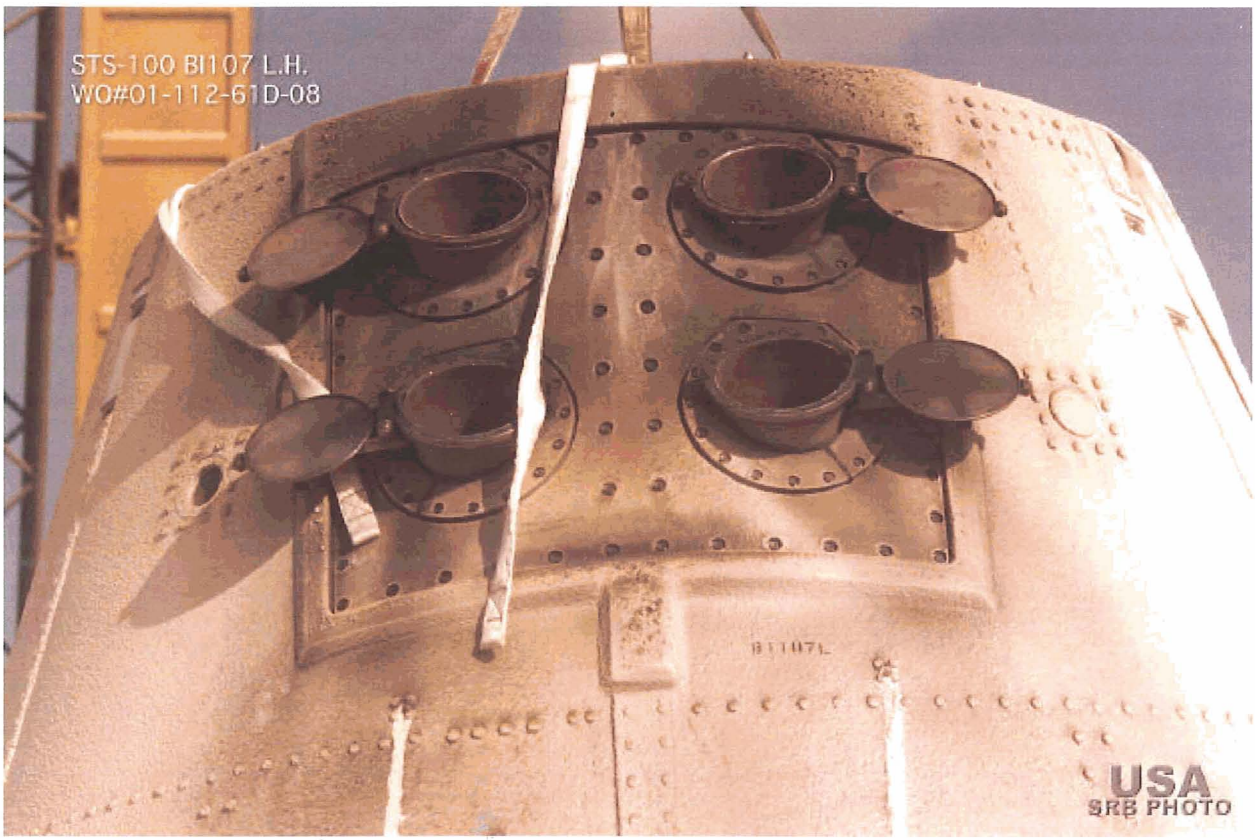
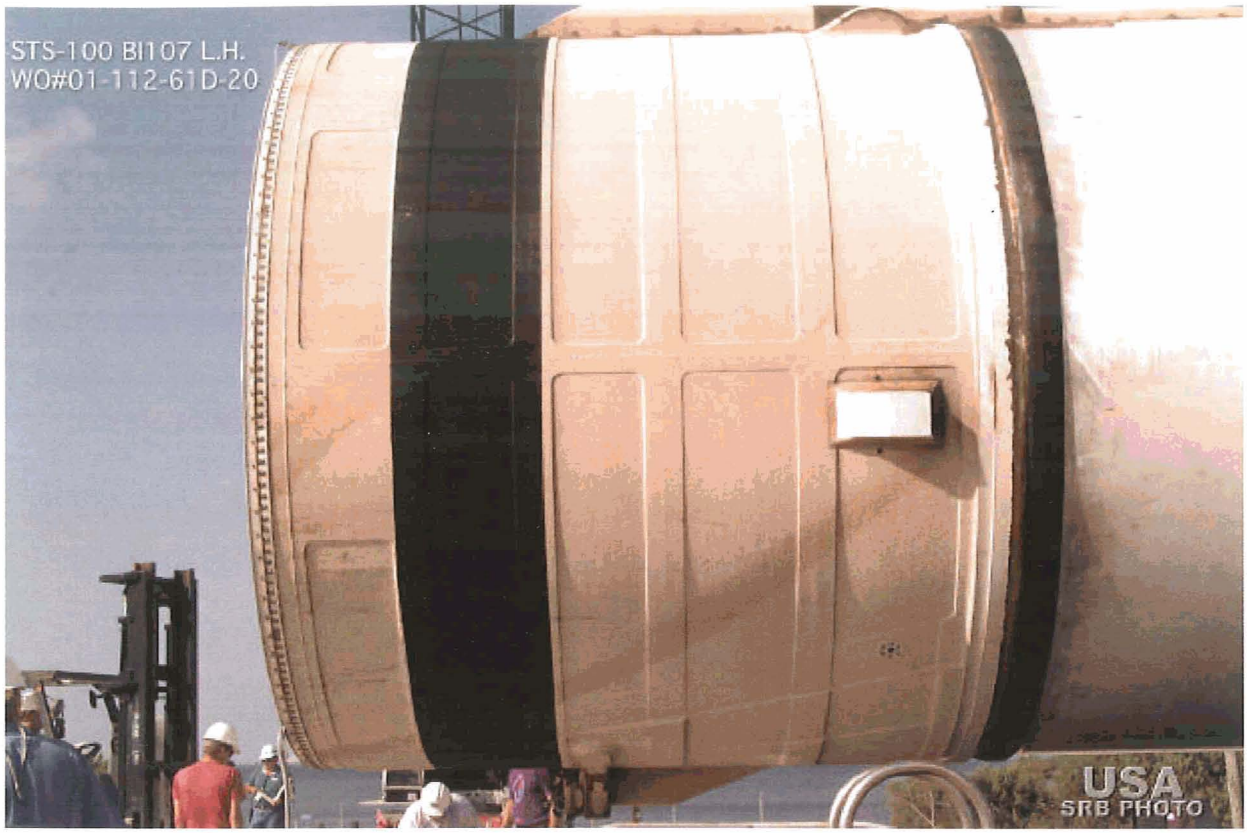


Photo 9: Frustum Post Flight Condition

The frustums exhibited no debonds/unbonds or missing TPS.
All eight BSM aero heat shield covers had locked in the typical opened position.



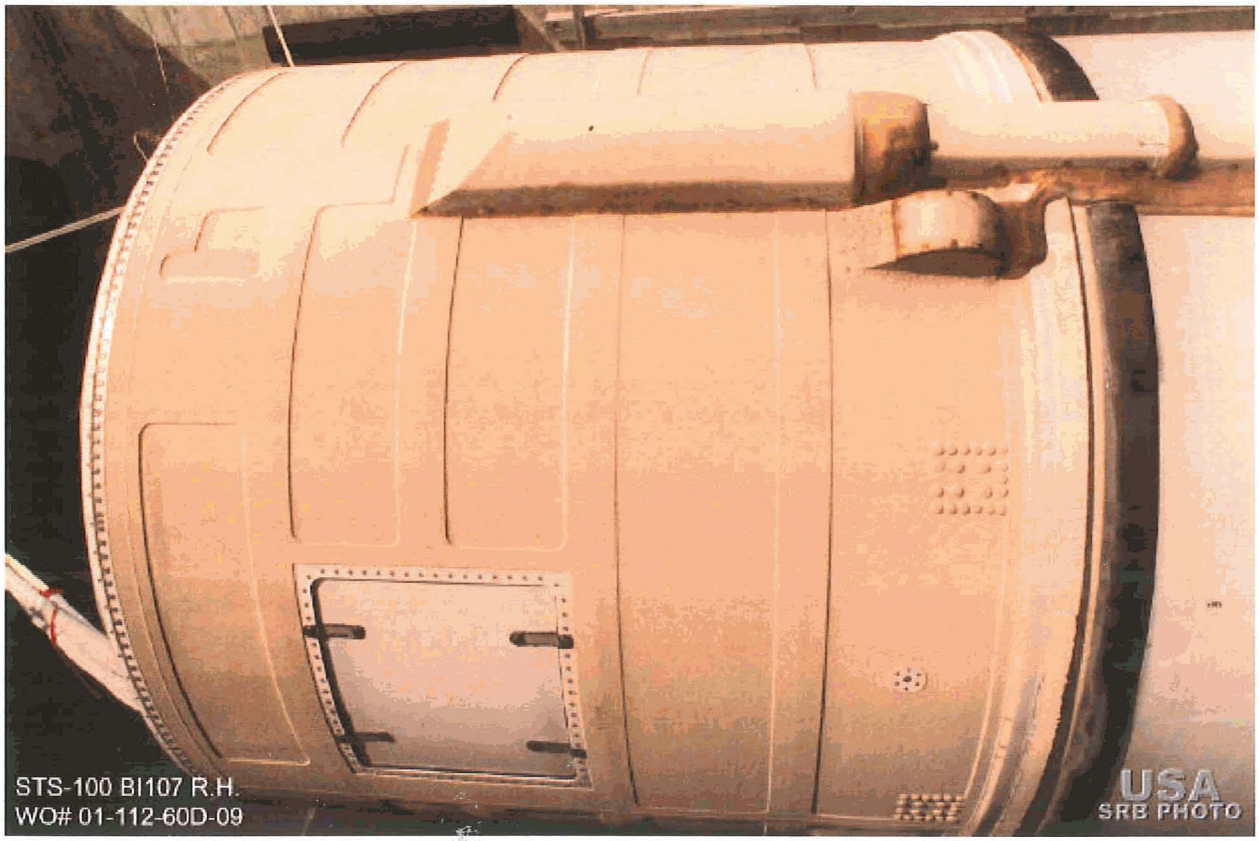


Photo 10: Forward Skirt Post Flight Condition

The forward skirts exhibited no debonds or missing TPS.

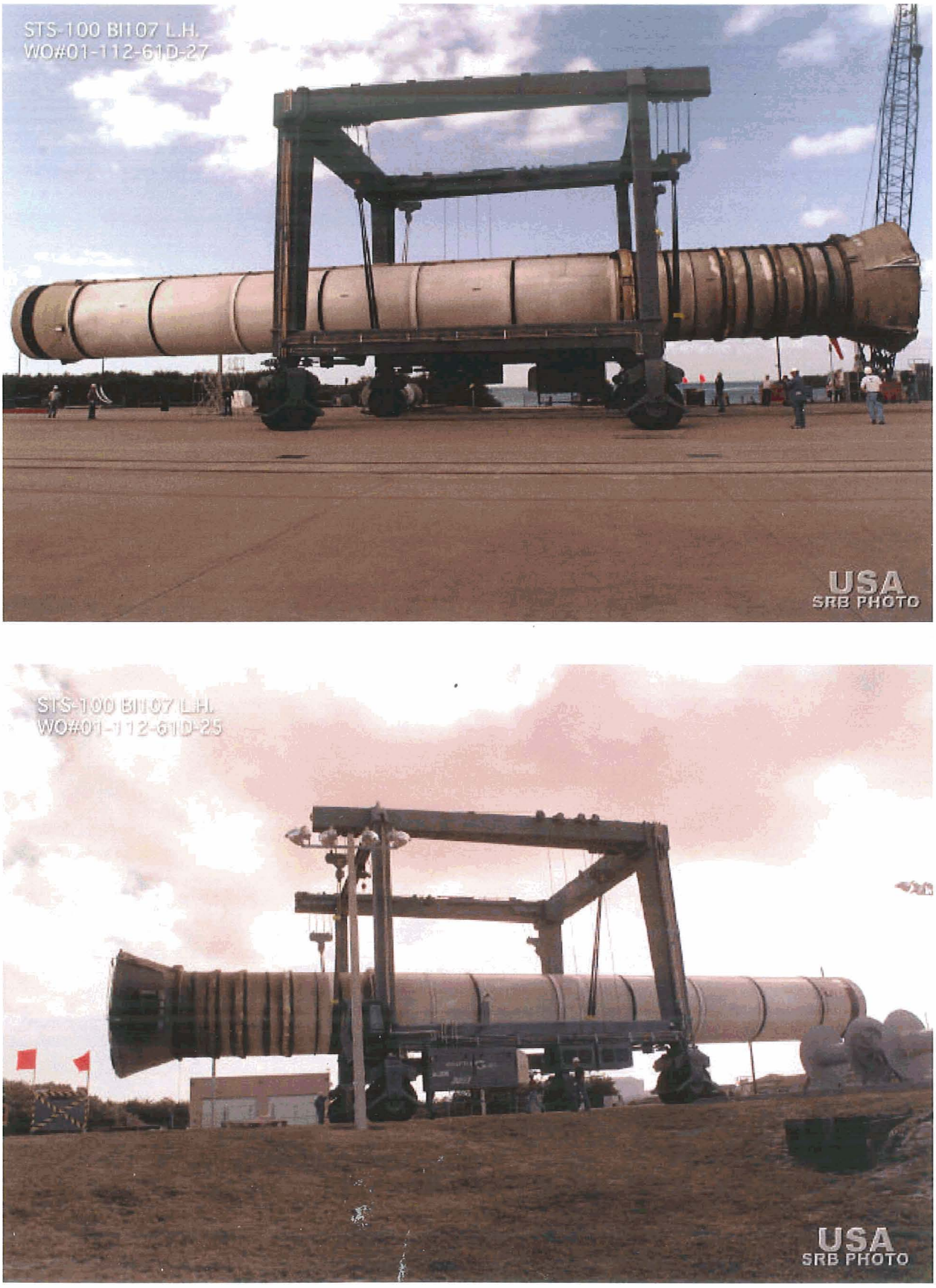


Photo 11: SRB Post Flight Condition

Both SRB's were found in good condition regarding debris assessment

7.0 ORBITER POST LANDING DEBRIS ASSESSMENT

After the 9:11 a.m. local/pacific time landing on 01 May 2001, a post landing inspection of OV-105 Endeavour was conducted at the Edwards Air Force Base on runway 22 and in the Mate/Demate Device (MDD). This inspection was performed to identify debris impact damage and, if possible, debris sources.

The Orbiter TPS sustained a total of 92 hits of which 13 had a major dimension of 1-inch or larger. This total does not include the numerous hits on the base heat shields attributed to SSME vibration/acoustics and exhaust plume recirculation.

The following table lists the STS-100 Orbiter damage hits by area:

	HITS > 1-inch	TOTAL HITS
Lower Surface	4	42
Upper Surface	0	0
Window Area	8	48
Right Side	0	0
Left Side	1	0
Right OMS Pod	0	2
Left OMS Pod	0	0
TOTALS	13	92

The Orbiter lower surface sustained 42 total hits, of which 4 had a major dimension of 1-inch or larger, both numbers are well within family. The majority of the lower surface damage sites occurred on the right-hand wing glove. Impacts in this area are most likely from LO2 feedline ice/frost or foam debris.

Although the number of hits on the left-hand lower surface were less than the right-hand lower surface, the largest lower surface tile damage was located on the left-hand wing glove forward of the main gear door. This shallow site measured 2.5-inches long by 1-inch wide by 0.125-inch deep, and is probably the result of impact by low density foam material.

A segment of Ames gap filler, located just aft of the nose gear wheel well, was protruding 0.5-inch. There was no indication of entry heating or tile damage. A second Ames gap filler from the nose gear door was found on the runway after wheel stop, to the left of the Orbiter approximately 10 feet outboard from the Orbiter wing glove. The gap filler showed no signs of entry reheating.

The OMS pods tiles had a typical amount of damage. No unusual tile damage or evidence of tile movement, as seen in lift-off films E-17 and -18, was observed on the OMS pods. However, a four-inch long segment of gap filler material was protruding from the left-hand OMS pod tiles by approximately 0.5-inch.

This is the third flight using the forward up-firing RCS jet plumes to help protect the windows from BSM particulate impingement during SRB separation. Hazing on windows 3 and 4 appeared to be greater than observed for the first two flights with the windows protection system. Quantitative evaluation of the window hazing will be provided through optical testing at KSC.

An AFRSI blanket was slightly de-bonded and protruding from the area immediately aft of the forward-firing jets in the forward RCS group.

Moderate hazing was noted on the upper portion of windows 2, 3, 4 and 5. In addition to hazing, streaks were observed on windows 3 and 4. The streaks are the result of impacts by RTV adhesive used on the forward RCS paper covers.

Damage sites on the window perimeter tiles were more than usual in quantity. There were a total of 48 hits on the window perimeter tiles with eight having dimensions greater than one inch. Damage to the window perimeter tiles on the forward facing windows is attributed to impact by RTV adhesive used on the forward RCS paper covers.

The main landing gear tires were reported to be in typical condition for a landing on a concrete runway. Ply under-cutting was observed on the outboard edges of both left-hand main gear tires.

ET/Orbiter separation devices EO-1, EO-2, and EO-3 functioned normally. No ordnance fragments were found on the runway beneath the umbilicals. The EO-2 and EO-3 fitting retainer springs appeared to be in nominal configuration.

There was less than usual amounts of tile damage on the base heat shield. The SSME Dome Heat Shield closeout blankets were in good condition. Slight fraying was observed on the SSME #3 blanket from the 10 to 12 o'clock position. Two large damage sites (approximately 3-inches by 3-inches) on the body flap upper surface tiles adjacent to the body flap stud, appear to be failed repairs.

The post-landing walkdown of the runway was performed by the rollout measurement team. All components of the drag chute were recovered and appeared to have functioned normally. Both reefing and line cutter pyrotechnic devices were expended.

In summary, both the total number of Orbiter TPS debris hits and the number of hits one-inch or larger were well within established family (reference Figures 3, 4 and 5).

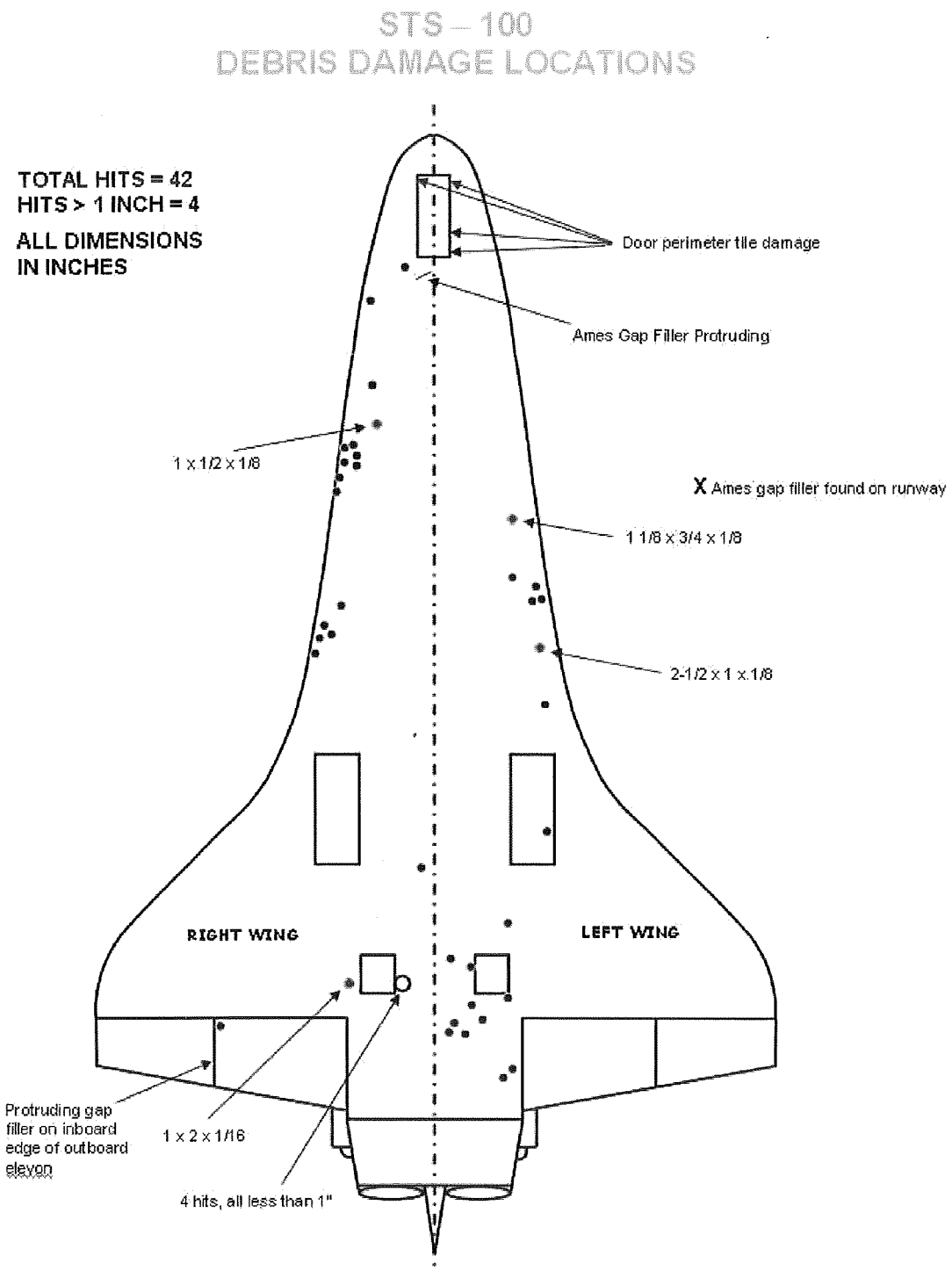


Figure 1: Orbiter Lower Surface Debris Damage Map

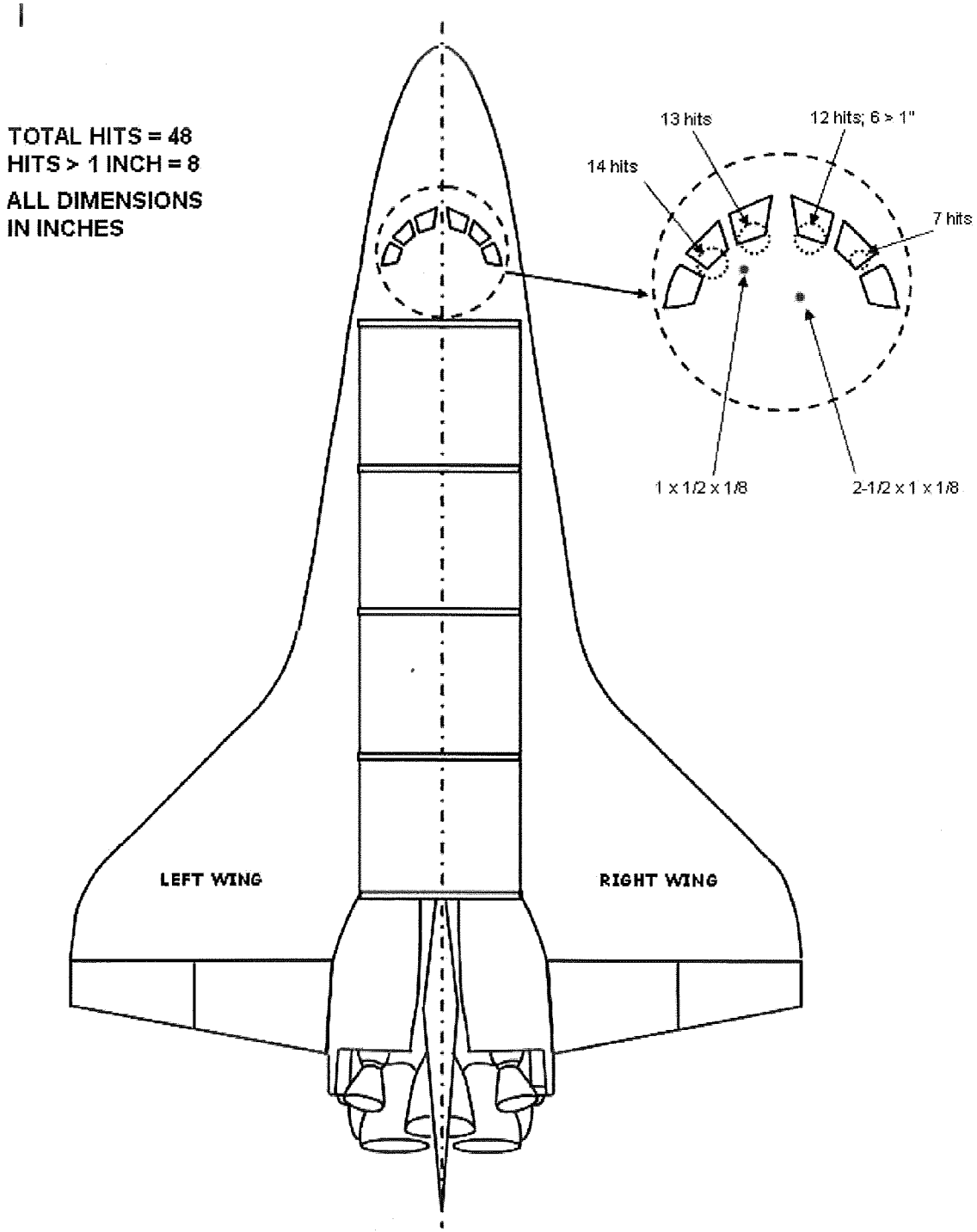


Figure 2: Orbiter Upper Surface Debris Damage Map

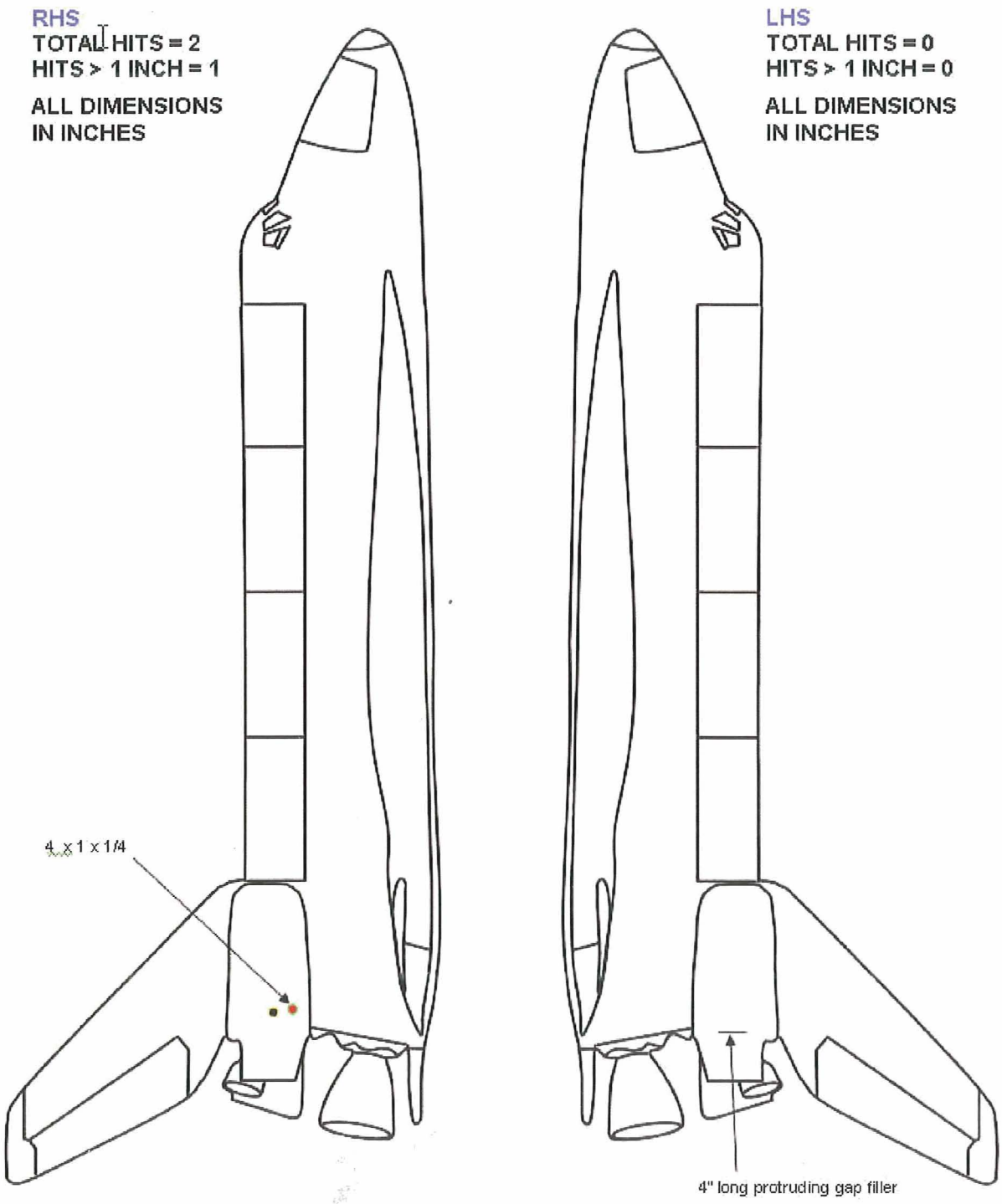
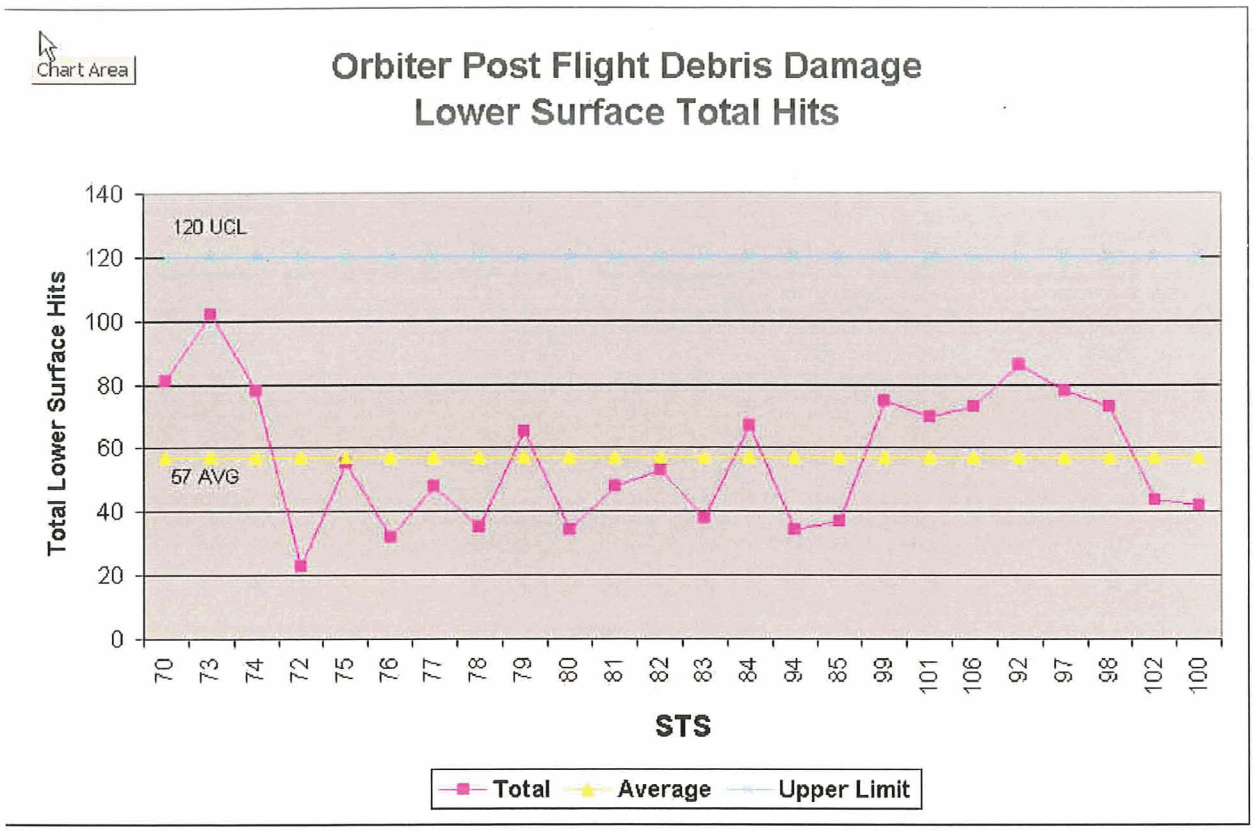


Figure 3: Overall View of Orbiter Sides

STS NUMBER	LOWER SURFACE		ENTIRE SURFACE	
	HITS > 1 INCH	TOTAL HITS	HITS > 1 INCH	TOTAL HITS
STS-70	5	81	9	127
STS-69	22	175	27	198
STS-73	17	102	26	147
STS-74	17	78	21	116
STS-72	3	23	6	55
STS-75	11	55	17	96
STS-76	5	32	15	69
STS-77	15	48	17	81
STS-78	5	35	12	85
STS-79	8	65	11	103
STS-80	4	34	8	93
STS-81	14	48	15	100
STS-82	14	53	18	103
STS-83	7	38	13	81
STS-84	10	67	13	103
STS-94	11	34	12	90
STS-85	6	37	13	102
STS-99	21	75	25	88
STS-101	19	70	27	113
STS-106	17	73	17	105
STS-92	14	86	24	127
STS-97	10	78	10	84
STS-98	8	73	13	102
STS-102	10	44	15	100
AVERAGE	11.4	62.7	16.0	102.8
SIGMA	5.6	31.7	6.1	28.0
STS-100	4	42	13	92

MISSIONS STS-86,87,89,90,91,95,88,96,93,103 ARE NOT INCLUDED SINCE THESE MISSIONS HAD SIGNIFICANT DAMAGE CAUSED BY KNOWN DEBRIS SOURCES

Figure 4: Orbiter Post Flight Debris Damage Summary



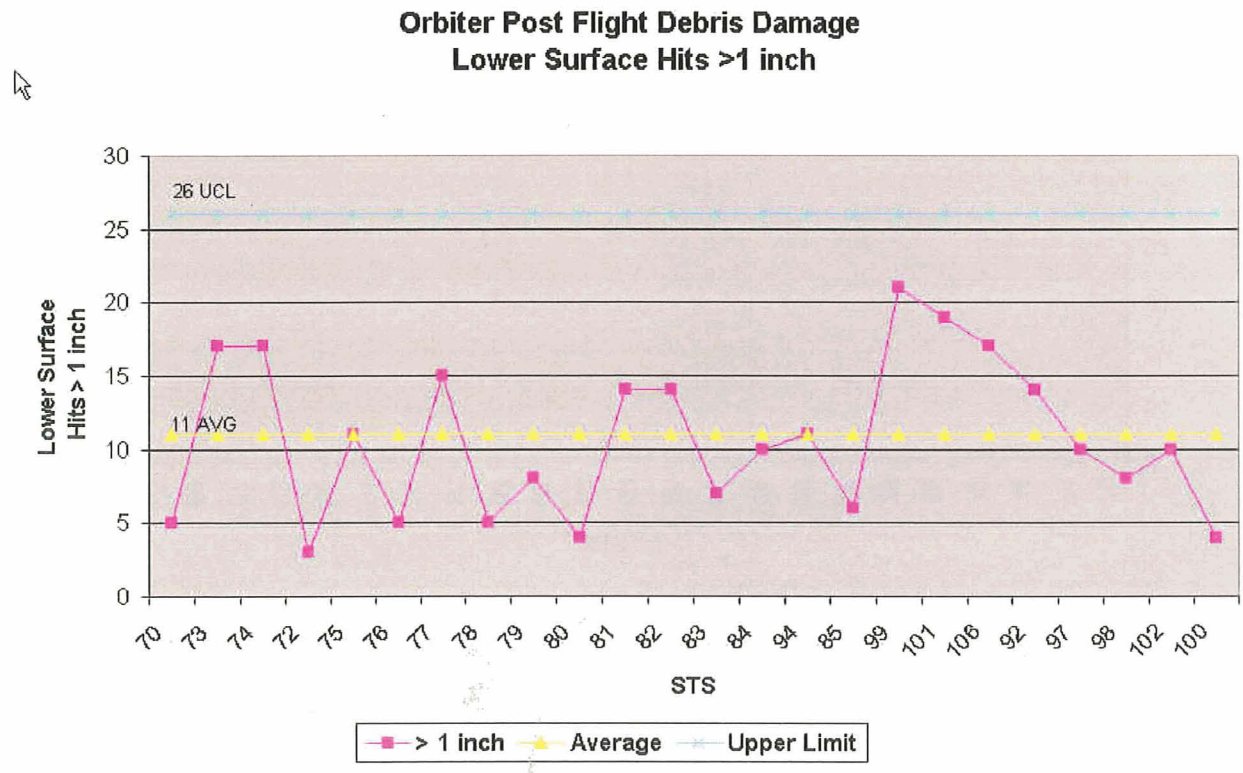
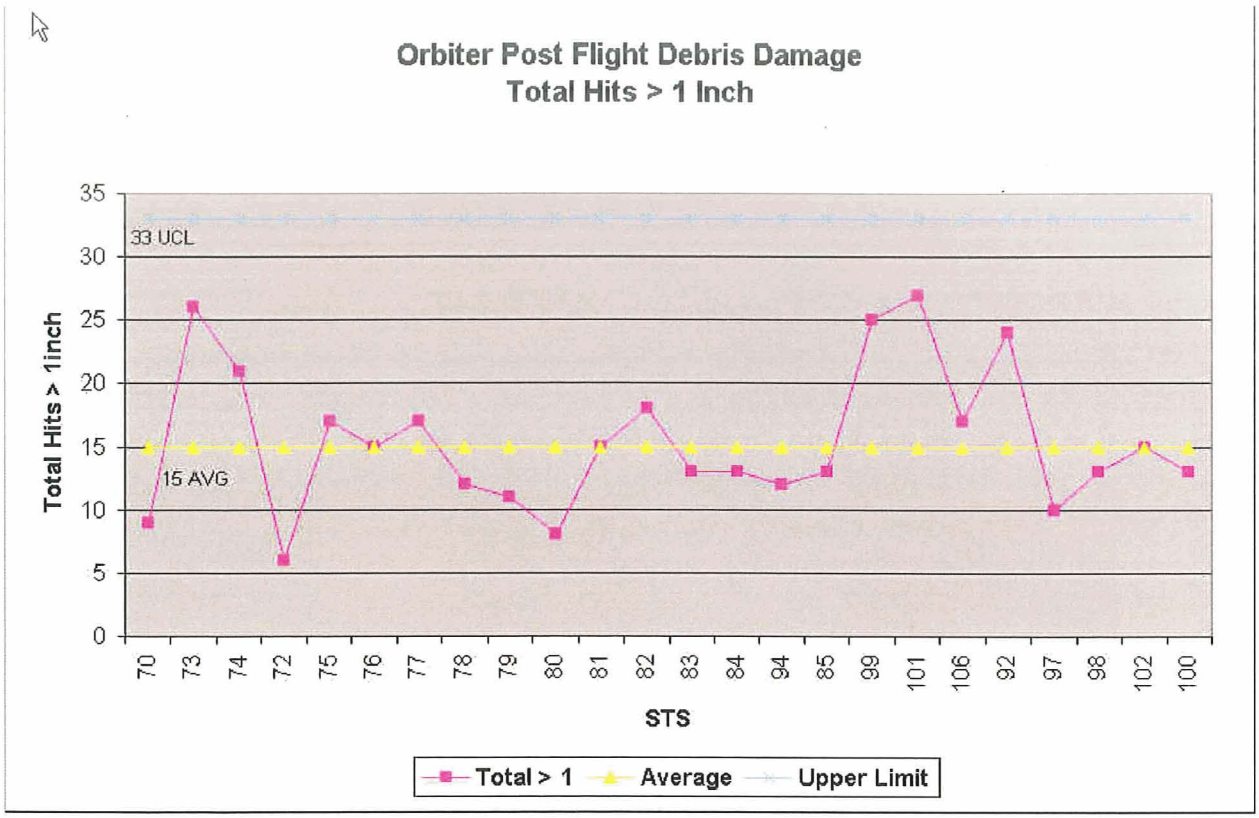


Figure 5: Control Limits for Lower Surface Hits



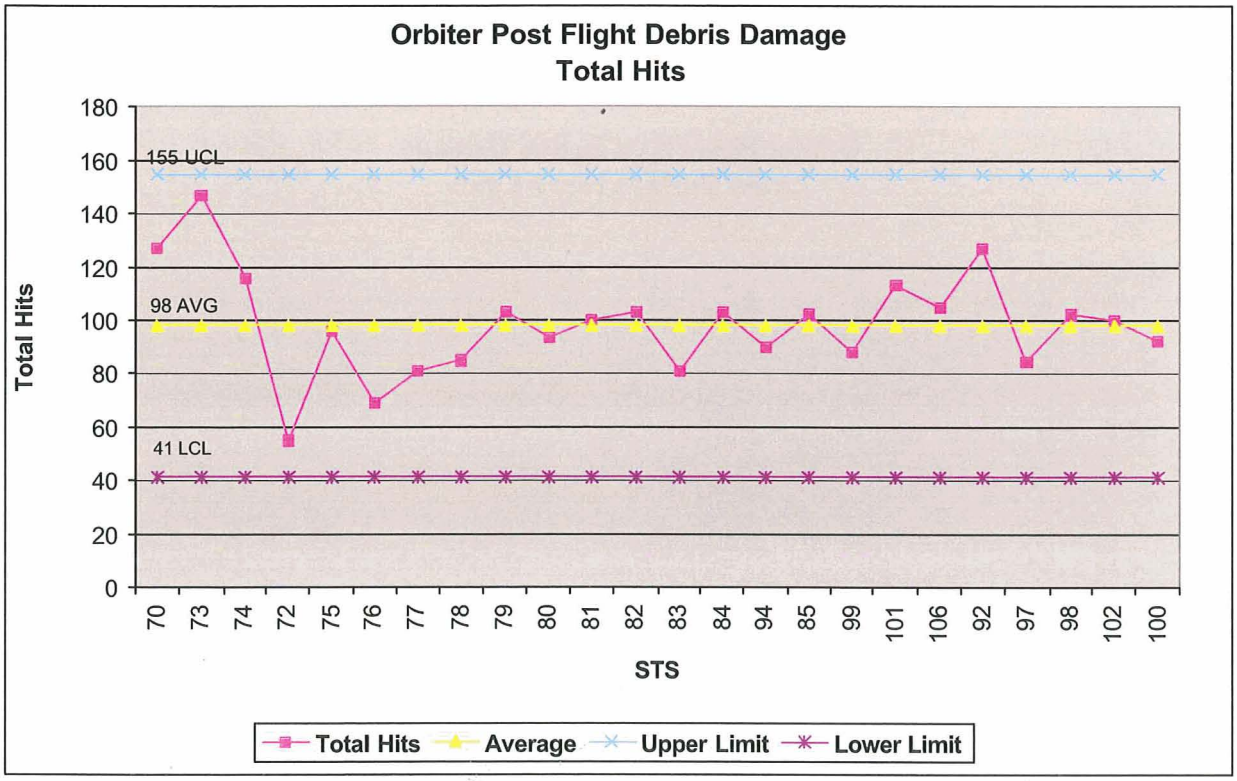


Figure 6: Control Limits for Total Hits

Photo 12: Overall View of Orbiter

The orbiter lower surface sustained only 42 total hits. Both the total number of Orbiter TPS debris hits and the number of hits 1-inch or larger were well within established family.

Photo 13: Damage to Lower Surface Tiles

The largest lower surface tile damage was located on the left-hand wing glove forward of the main gear door. This shallow site measured 2.5-inches long by 1-inch wide by 0.125-inch deep, and is probably the result of impact by low density foam material.

Photo 14: LO2 ET/ORB Umbilical

Photo 15: LH2 ET/ORB Umbilical

Photo 16: LH OMS Pod TPS

The OMS pods tiles had a typical amount of damage. No unusual tile damage or evidence of tile movement, as seen in lift-off films, was observed on the OMS pods.

8.0 DEBRIS SAMPLE LAB REPORTS

Window wipe samples from Orbiter windows 1 thru 8 and tile damage site samples from Orbiter window 4 carrier panel were submitted to the KSC Microchemical Analysis Branch (MAB) for material/chemical identification analysis and comparison to known STS materials. The results of this analysis are summarized by sample location.

Window samples provided indication of Orbiter Thermal Protection System (TPS), metallics and metallic corrosion, natural landing site, and window polish residue materials.

The tile damage site samples provided indication of Orbiter TPS materials.

Post-landing sample results provided no new information or trend data for debris source analysis.

9.0 POST-LAUNCH ANOMALIES

Based on the debris walkdowns and film/video review, two post launch anomalies were observed on the STS-100 mission.

9.1. LAUNCH PAD

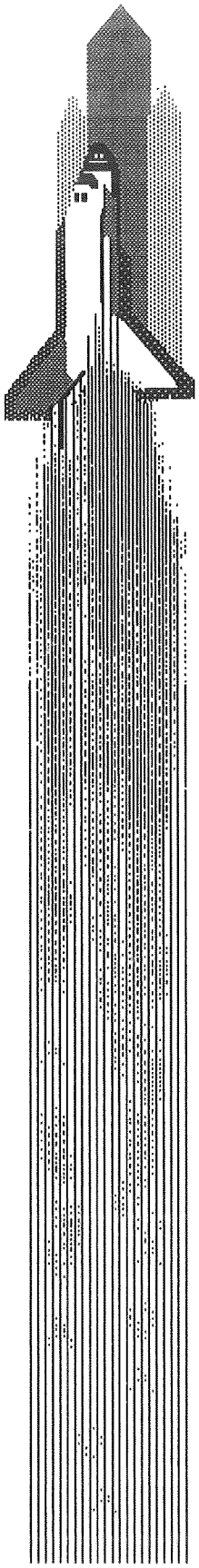
The GH2 vent arm deceleration cable failed to catch the spool weldment. IPR Pad A -2171 was picked up to document and trouble-shoot the anomaly. No conclusive cause could be determined in the analysis and the IPR was closed as an unexplained anomaly.

9.2 ORBITER

Due to the motion observed during the film review on the LH OMS Pod Based post-landing inspections were performed on the OMS Pod structure and TPS. Inspections revealed no damage to the TPS or underlying structure of the OMS Pod.

APPENDIX A. JSC PHOTOGRAPHIC ANALYSIS SUMMARY

image science & analysis group
nasa-jsc



Space Science Branch

STS-100 Summary of Significant Events

June 14, 2001

image science & analysis group
nasa-jsc

Space Shuttle
STS-100 Summary of Significant Events

Project Work Order - SN3CS

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Table of Contents

1. STS-100 (OV-105): Film/Video Screening and Timing Summary

1.1 Screening Activities

1.1.1 Launch

The STS-100 launch of Endeavour (OV-105) from Pad 39A occurred on Thursday, April 19, 2001 at approximately 109:18:40:41.998 UTC as seen on camera E9. SRB separation occurred at approximately 18:42:45.35 UTC as seen on camera KTV13.

On launch day, 23 videos were received and screened. (Camera ET208 is no longer provided).

Twenty launch films were screened and a report was sent to the Shuttle Program distribution on April 23, 2001. Twenty additional films were received for contingency support and anomaly resolution. Films E15, E77, and E223 were not received.

One anomalous event was seen during the review of the STS-100 launch films that was elevated to the Launch + 4 Day KSC, JSC, MSFC Film/Video Analysis Teams Consolidated Film Review Report: CFVR-100-1: OMS Pod vibration at SSME startup.

No anomalous events were seen during the review of the STS-100 landing films and the on-board films of the External Tank that were elevated to the Landing + 3 Day KSC, JSC, MSFC Film/Video Analysis Teams Consolidated Film Review Report. (These reports consolidate the multi-center post flight photo reviews into a single list of observations for engineering review. This integrates the photo review process into the IFA / PRACA process to ensure that the identified observations are assessed and dispositioned prior to the next flight per established problem reporting criteria.)

The 16mm umbilical well cameras flew on OV-105 during STS-100. The 35mm umbilical well TPS camera film and the crew handheld still photography and video of the External Tank were acquired. See Section 2.3.

1.1.2 On-Orbit

No unplanned on-orbit Shuttle support tasks were requested.

Pre-planned real-time analysis support was provided to the ISS AF-6A Space Station photographic and television external survey. The Space Station image analysis support will be documented in the AF-6A Imagery Overview Report.

1.1.3 Landing

Endeavour made a day landing on runway 22 at Edwards Air Force Base (EAFB) on May 1, 2001 at 16:10:42.298 UTC. This was the third time since March 1996 that an Orbiter has landed at EAFB (STS-92 and STS-98 also landed at EAFB). Four public affairs landing videos with actual landing times were received. The engineering television replays were not received. Nine landing films were received.

The landing touchdown appeared normal. The drag chute deploy sequence appeared normal on the landing imagery. Using available video including NASA-Select, no anomalous events were seen during the Orbiter approach, landing, and landing rollout.

Post landing, a sink rate analysis of the STS-100 main landing gear was performed for the main gear touchdown. See Section 2.5.

According to the pre-mission agreement, the STS-100 landing films were not screened due to budgetary constraints.

2. Summary of Significant Events

2.1 KSC, JSC, MSFC Film / Video Analysis Teams Consolidated Film Review Reports

One anomalous event was noted during the screening of the STS-100 launch films that was reported in the Launch +4 day KSC, JSC, MSFC Film / Video Analysis Teams Consolidated Film Review Report. No anomalies were reported in the Landing +3 day KSC, JSC, MSFC Film / Video Analysis Teams Consolidated Film Review Report.

CFVR-100-1: OMS Pod Vibration at SSME Start-up - Imagery Analysis of the STS-100 Flexing of the Left OMS Thermal Protection System (TPS) Tiles

Flexing of the thermal protection system (TPS) tiles on the left (port) OMS thruster pod during STS-100 just prior to liftoff was observed and measured using high-speed motion picture film obtained from camera E18. This flexing was seen at main engine ignition at a time between –3.8 seconds MET and –3.0 seconds MET (18:40:38.2 to 18:40:39.0 UTC). The tiles appeared to bulge outward or pulse rhythmically at high frequency and there was a corresponding increase and decrease in the size of the dark area between some adjacent tiles lying in the center of the region. Similar, but much less dramatic pulsing was seen on the right (starboard) OMS pod tiles from camera E17, an identical camera on the other side of the Orbiter. The view of the right OMS pod tiles contains significant noise and less contrast, and so was not analyzed.

Figure 2.1(A) Camera E18 View of Left OMS TPS Tiles
and an Enlarged View of the Area of Interest.

Cameras E18 and E17 are fitted with a 10 mm lens and capture approximately 400 frames per second on 16 mm film. Figure 2.1(A) (left) is a wide view from camera E18 showing the area where the tile flexing was observed with Figure 2.1 (A) (right) showing an enlarged view of the analysis area. For the analysis, 300 still frames were digitized by the Marshall Space Flight Center Engineering Photographic Analysis team and were received electronically.

The motions of two tile corners (Figure 2.1 (A), right) in the center of the panel were measured relative to a reference point on the bottom, or aft, edge of the panel. The reference point was necessary to remove translational camera jitter, which was 3-4 times greater, in pixels, than the vibrational motion of the tiles. Rotational camera jitter was assumed to be negligible.

Scale in inches per pixel in the direction out of the plane of the tiles was derived using the design coordinates for several of the tiles combined with the location of the camera, all in the Orbiter structural coordinate system. This vector analysis gave a scale of 0.25 (+/-0.015) inches per pixel in the out-of-plane direction. This direction, as projected onto the image, was oriented 40 degrees counter-clockwise from the image horizontal.

The motions of both mid-panel points in the out-of-plane direction showed maximum deflections of 0.7 inches for any single movement (implying a zero-to-peak amplitude of 0.35 inches) occurring just after 18:40:38.6 UTC. See Figure 2.1(B).

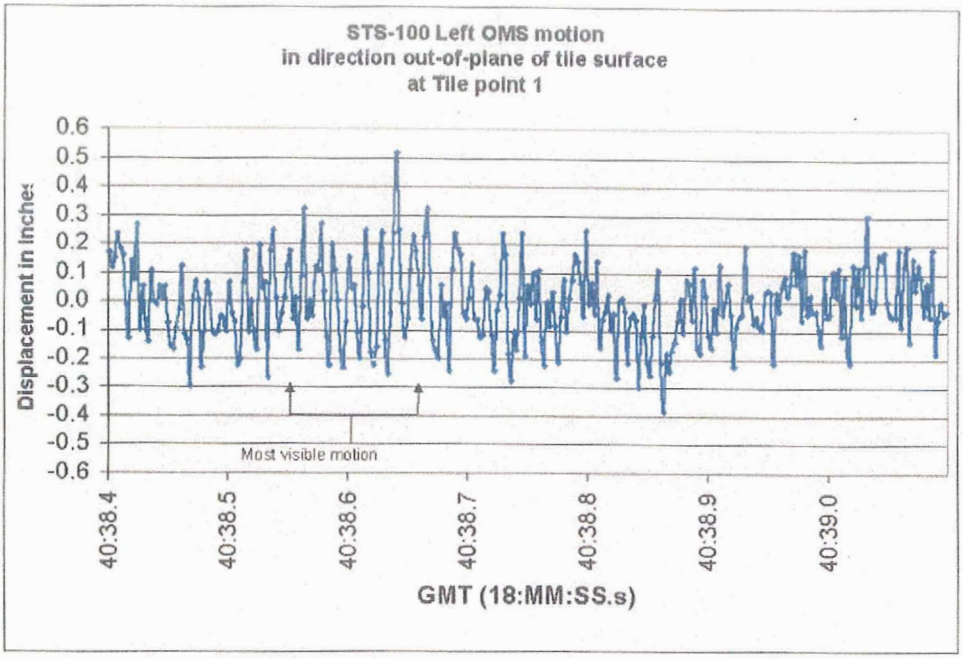

Figure 2.1(B) Tile Displacement in Inches

Power spectral density plots for these motions show strong 72-73 hertz oscillations. See Figure 2.1(C). Similar spectral plots for the motion component that is perpendicular to this direction in the image show no dominant frequency of oscillation. Tracking uncertainty was estimated to be +/- 0.15 inches.

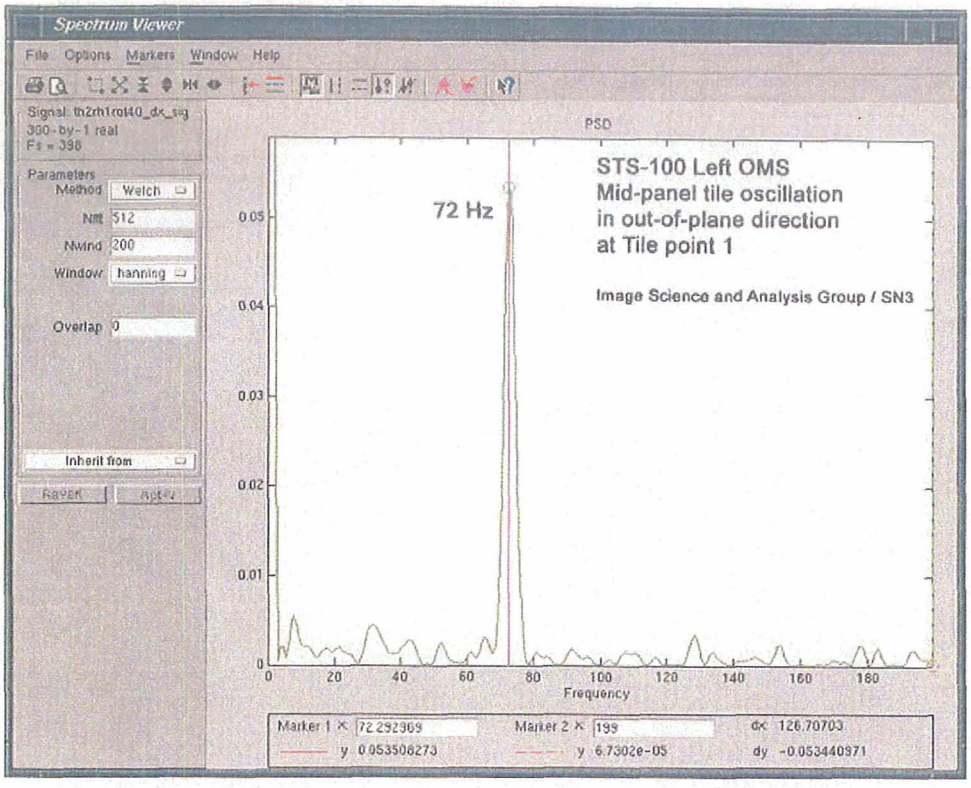

Figure 2.1(C) Frequency Plot of Tile Motion

Previous mission films were screened for visual indications of OMS Pod vibrations similar to that seen on STS-100. However, no motions of the magnitude of that seen on the left STS-100 OMS pod were found. (The previous missions screened were STS-77, STS-80, STS-83, STS-89, STS-94, STS-97, and STS-98)

2.2 Other Launch Observations

2.2.1 Debris from SSME Ignition through Liftoff

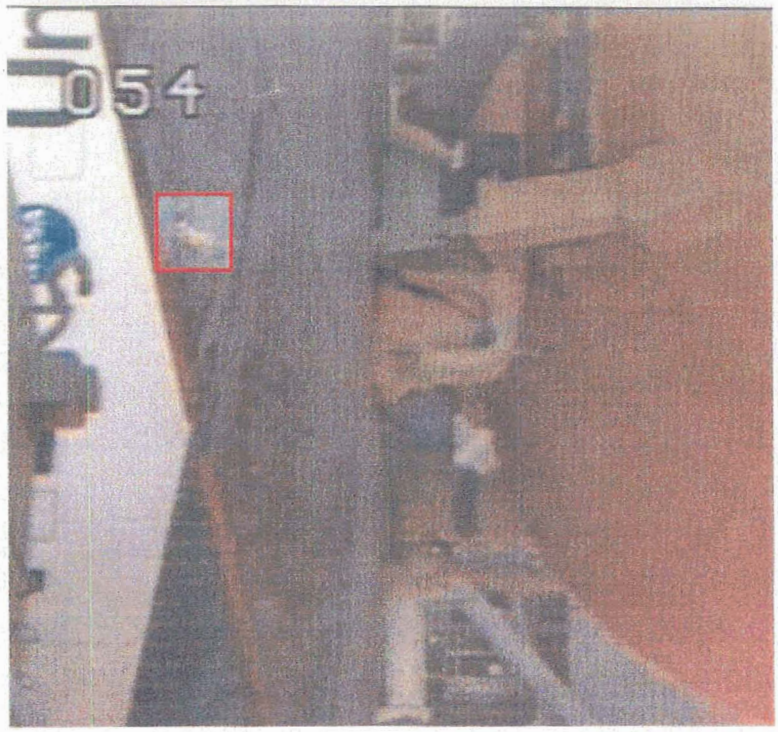

Figure 2.2.1 (A) Debris seen near Right Outboard Elevon. (Camera OTV054)

A single piece of debris first seen near the right outboard elevon moved in a –Z direction between the ET aft dome and the RSRB during SSME ignition. This debris was not identified but it was possibly a piece of RCS paper (18:40:37.893 UTC). (Camera OTV054)

Figure 2.2.1 (B) Debris seen near +Y Vertical Strut. (Camera OTV054)

Several pieces of white-colored debris (probable frost) were seen falling aft from the aft surface of the ET +Y vertical strut during SSME ignition (18:40:38.994 UTC). See Figure 2.2.1 (B). (Camera OTV054)

Several pieces of frost/ice debris were seen falling from the vicinity of the LSRB vertical attach strut aft along the LSRB during liftoff (18:40:42.994 UTC). (Camera E31)

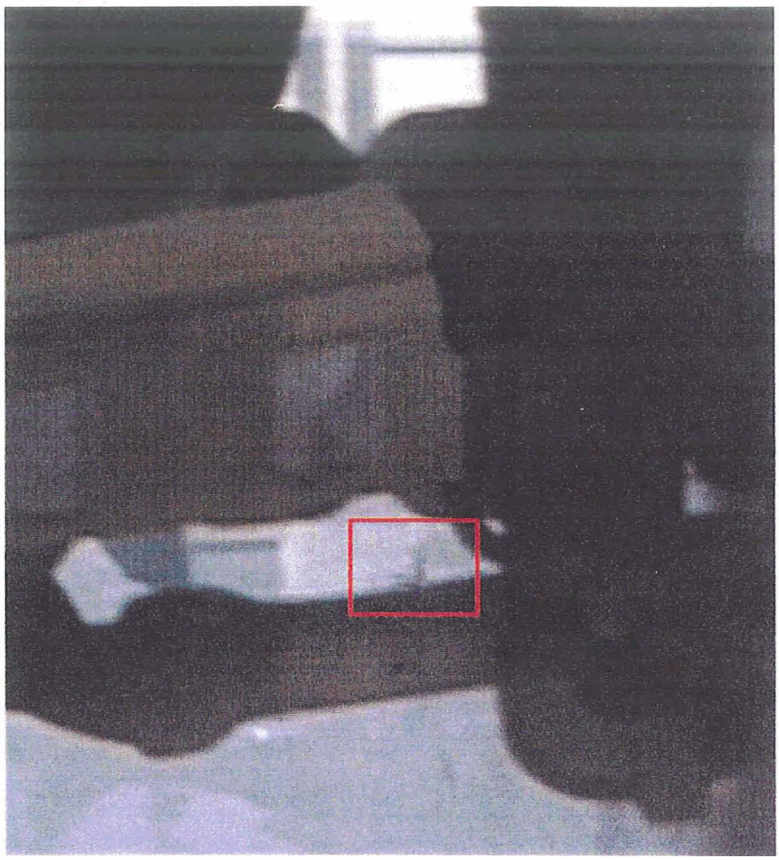

Figure 2.2.1 (C) Ice Debris seen Contacting the LH2 Recirculation Line. (Camera OTV063)

Multiple pieces of ice debris were seen falling from the ET/Orbiter umbilicals and along the –Z side of the body flap during SSME ignition through liftoff. Umbilical ice debris was seen to contact the –Y edge of the Orbiter LH2 umbilical well doorsill (18:40:42.898 UTC). Umbilical ice was also seen contacting the forward surface of the 4-inch LH2 recirculation line (18:40:39.095 UTC). See Figure 2.2.1 (C). No damage to the launch vehicle was detected. Umbilical ice debris contacting the Orbiter LH2 umbilical well doorsill and the 4-inch LH2 recirculation line has been seen on previous missions. (Cameras OTV009, OTV049, OTV050, OTV054, OTV061, OTV063, E1, E4, E5, E18, E20, E31, E34, E54, E63, E76)

A light-colored piece of debris (probably RCS paper) was seen aft of the right RCS stinger at liftoff (18:40:43.032 UTC). (Camera OTV049)

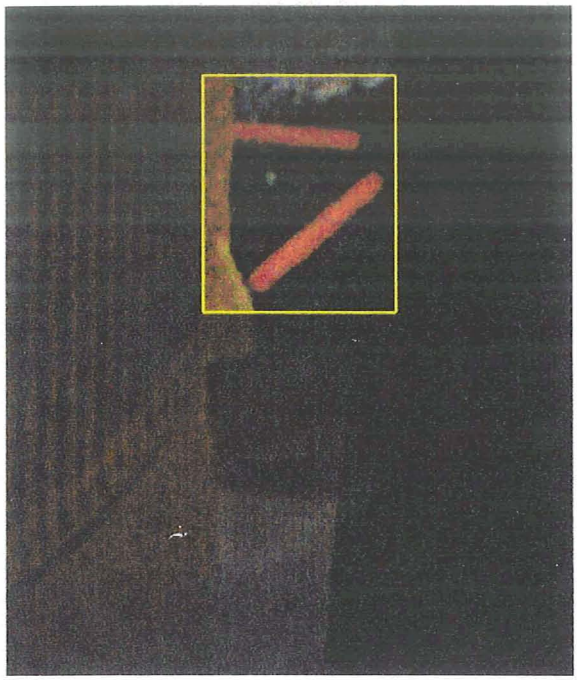

Figure 2.2.1 (D) Debris near ET/Orbiter Forward Attach Bipod. (Camera E34)

A single piece of light-colored debris was seen falling aft of the ET/Orbiter forward attach bipod during liftoff. This debris was probably ice from the forward ET LO2 feed line bellows (18:40:44.700 UTC). (Cameras OTV061, E34)

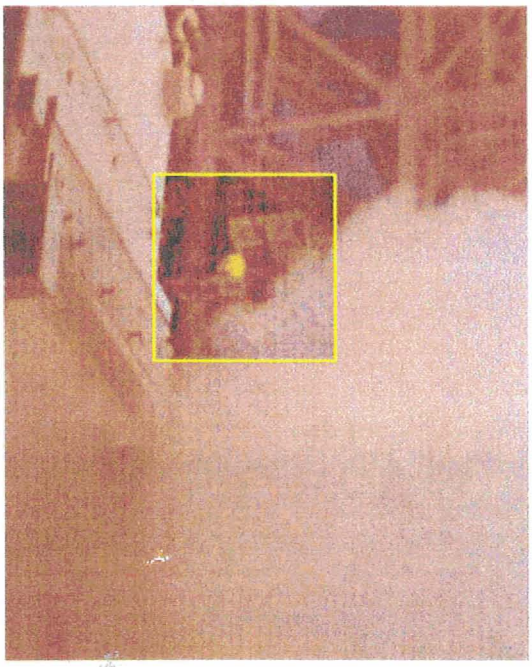

Figure 2.2.1 (E) Debris seen moving away from the SLV during Liftoff. (Camera E5)

A single, large piece of debris (probably SRB aft skirt instafoam) was seen moving away from the SRB's during liftoff (18:40:44.676 UTC). (Cameras E5, E18)

Several pieces of light-colored debris and a piece of probable water baffle debris were seen in the exhaust cloud after liftoff (E1, 18:40:44.074 UTC). (Cameras E1, E31, E20, E63)

A single light-colored piece of unidentified debris was seen above the LO2 TSM and near the RSRB aft skirt during liftoff. (Camera E76)

Figure 2.2.1 (F) Debris seen above LH2 TSM during Liftoff. (Camera OTV009)

Two pieces of light-colored, irregular-shaped unidentified debris were seen above the LH2 TSM during liftoff (18:40:44.7 UTC). (Camera OTV009)

2.2.2 Debris During Ascent

As observed on previous missions, multiple pieces of debris (umbilical ice and RCS paper) were seen near the SSME exhaust plume and falling aft of the launch vehicle during ascent. Also during ascent, several pieces of light-colored debris (probably umbilical ice) were seen along the -Z side of the body flap. Examples are (Camera ET207, E52, E54, E222, E224):

18:40:50.038 UTC - A single piece of RCS paper debris from a right up-firing RCS jet fell into the SSME exhaust plume
18:40:52.958 UTC - A single piece of RCS paper debris from left RCS stinger fell aft across +Z surface of left wing
18:40:56.884 UTC - A single piece of RCS paper debris was seen falling aft across the +Z surface of the left wing
18:40:57.183 UTC - Probable RCS paper debris seen near vertical stabilizer
18:40:58.722 UTC - Single piece of RCS paper debris first seen near the base of the vertical stabilizer and fell aft into the SSME plume
18:40:59.119 UTC - Debris near base of LSRB falling toward SSME plume
18:41:00.256 UTC - Probable RCS paper falling along port side of Orbiter
18:41:03.423 UTC - Probable umbilical ice falling along body flap
18:41:14.130 UTC - Debris in SSME exhaust plume
18:41:17.771 UTC - Multiple pieces of light-colored debris near body flap
18:41:18.972 UTC - Probable RCS paper debris near rim of SSME #3
18:41:19.639 UTC - Light-colored debris between SSME's and body flap
18:41:25.212 UTC - A single piece of light colored debris was seen exiting the SRB exhaust plume

As on previous missions, debris was seen exiting the SRB exhaust plumes. The debris exiting the SRB exhaust plumes during the majority of the ascent was probably instafoam from the aft end of the SRB's. The more dense appearing debris near the time of tail-off, just prior to SRB separation, was probably SRB slag debris. Examples are:

ET204 - 18:42:06.733 UTC
E207 - Frames 7330, 7440
E212 - Frame 443
E220 - Frame 13160
E223 - Frames 7445

A ring-shaped object (approximately the diameter of the SRB throat) was noted traveling from the RSRB and along the SRB exhaust plume (frames 8075-8210). The object was concluded to be a piece of slag debris that appeared to have a ring-like structure due to atmospheric conditions. (Camera E207)

2.2.3 Mobile Launch Platform (MLP) Events

The SSME ignition appeared normal on the film and video views and the SSME Mach diamonds appeared to form in the expected sequence (3,2,1). The times for the Mach diamond formation given in Table 2.2.3 are from film E76. (Cameras OTV051, OTV070, E76)

SSME	TIME (UTC)
SSME #3	18:40:38.766
SSME #2	18:40:38.796
SSME #1	18:40:38.956

Table 2.2.3 SSME Mach Diamond Formation Times

Orange vapor (possibly free burning hydrogen) was seen forward of the SSME rims, near the base of the vertical stabilizer, and in the vicinity of the drag chute door during SSME ignition (18:40:36.759 UTC). Orange vapor forward of the SSME rims has been seen on previous mission films and videos. (Cameras OTV070, E2, E5, E19, E63)

Frost was seen at the base of SSME #2 during ignition and liftoff. This event has been seen on previous mission films. (Camera E19, E20)

Movement of the SSME #2 Dome Mounted Heat Shield (DMHS) was visible during SSME ignition (18:40:38.527 UTC). Similar motion has been seen on previous mission films and videos. (Cameras OTV070, E17)

Two orange-colored streaks were seen in the SSME exhaust plume during liftoff (18:40:44.4 and 18:40:44.7 UTC). (Camera OTV009)

Numerous birds were visible on the east, west, and south sides of the launch vehicle during liftoff. (Camera KTV4A)

Typical of previous missions, small areas of tile surface coating material erosion were seen on the base heat shield outboard of SSME #3 (18:40:37.3, 18:40:38.626 UTC) and on the base heat shield outboard of SSME #2 (18:40:38.2 UTC). (Cameras E17, E20)

SRB ignition was at 18:40:41.998 UTC based on the observation of the PIC firing at RSRB holddown post M-1. (Camera E9)

2.2.4 Ascent Events

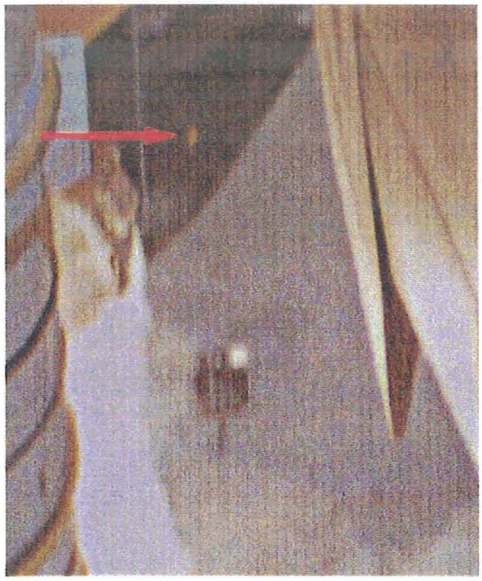

Figure 2.2.4 (A) Detached Umbilical Purge Barrier Material. (Camera E34)

A relatively large single-piece of light-orange-colored umbilical purge barrier material was seen detaching from the LH2 ET/Orbiter umbilical during liftoff (18:40:45.506 UTC). (Camera E34) Detached umbilical purge barrier material has been seen on previous mission imagery.

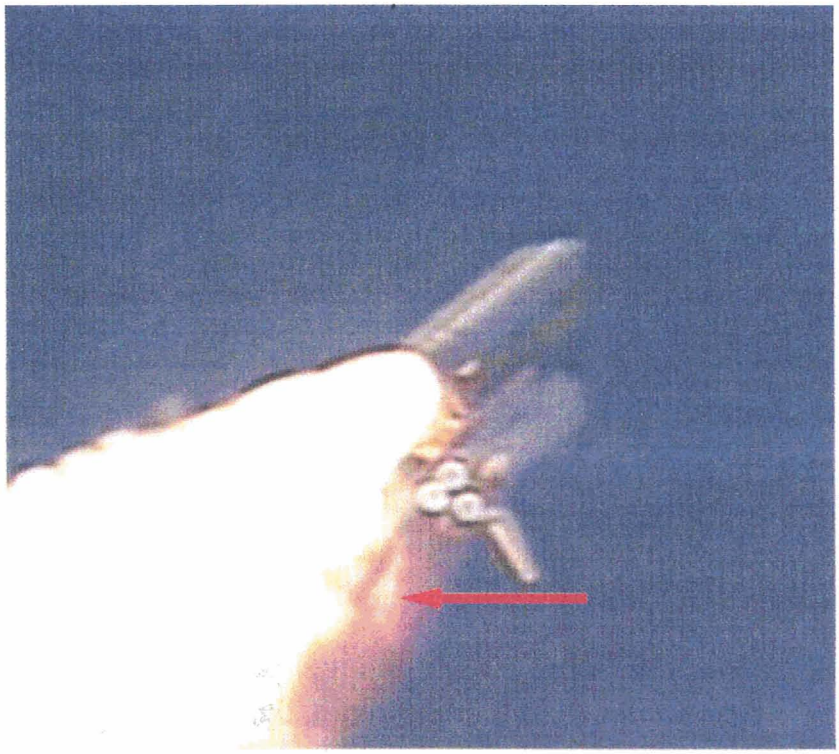

Figure 2.2.4 (B) Flare seen in SSME Exhaust Plume. (Camera KTV4A)

Multiple light-orange-colored flares (possibly debris induced) were noted in the SSME exhaust plume during ascent on the intermediate and long range tracking camera films. Often on previous mission imagery, debris has been seen contacting the SSME exhaust plume resulting in visible flares. Usually this debris is RCS paper. (On STS-26 and STS-101, debris that resulted in very large orange-colored flares was determined to have been tile material.) Examples of flares seen on STS-100 are (Cameras KTV4A, ET207, E54, E207, E220, E222, E224):

18:40:48.861 UTC
18:40:57.717 UTC
18:41:01.017 UTC
18:41:11.197 UTC
18:41:15.674 UTC
18:41:15.765 UTC
18:41:15.798 UTC
18:41:23.782 UTC
18:41:24.316 UTC
18:41:24.583 UTC
18:41:24.650 UTC
18:41:26.246 UTC

Flares in the SSME exhaust plumes have been seen on previous missions films and videos.

A vapor streak was seen near the forward RSRB stiffener ring during ascent (18:41:11.298 UTC). (Camera ET207)

Body flap motion was visible during ascent (18:41:00.2 to 18:41:45.8 UTC). The body flap motion was less apparent than that seen on STS-97 and STS-98. This may be at least partially due to the soft focus of the long range tracking views (probably due to atmospheric haze). No follow-up analysis was requested. (Camera ET207, E207)

Recirculation, or the forward expansion of burning gasses near the ET aft dome, was very evident during later ascent (18:42:11.958 to 18:42:31.908 UTC). Recirculation has been seen on previous mission films and videos. (Camera ET207, ET212)

A new procedure was implemented by the Shuttle Program to fire the forward RCS thrusters during SRB separation in order to help keep the Orbiter windows free of exhaust particle hazing. The effects of the firing of the forward RCS were not visible in the exhaust plumes near the forward end of the Orbiter on STS-100. This could possibly be due to the soft focus on the long range tracking films (Camera ET207, E207).

Orange vapors from the early OMS-2 assist burn were visible approximately 10.1 seconds after SRB separation (Cameras E207, E212 frame 8343).

2.3 Onboard Photography of the External Tank (ET-108A)

2.3.1 16mm Umbilical Well Camera Films

Two rolls of the STS-100 16mm umbilical well film were received. No anomalous events were seen. The film quality was very good on the two 16mm umbilical well camera films. However, one of the films (FL101) was cut off just after ET separation due to a film jam.

The LSRB separation appeared normal on the 16mm umbilical well camera films. Numerous light-colored pieces of debris (insulation), and dark debris (charred insulation) were seen throughout the SRB separation film sequence. Typical ablation and charring of the ET/Orbiter LH2 umbilical electric cable tray and the aft surface of the -Y upper strut fairing prior to SRB separation were seen. Pieces of TPS were seen to detach from the aft surface of the horizontal section of the -Y ET vertical strut. A long, flexible irregular-shaped, rope-like object was seen detaching from an unidentified location near the base of the LH2 umbilical prior to SRB separation (possibly a piece of umbilical purge barrier tape). Normal blistering of the fire barrier material on the outboard side of the LH2 umbilical was seen. Divoting of the TPS on the aft dome was also noted.

The ET separation from the Orbiter appeared normal. Typical vapor and multiple light colored pieces of debris were seen after the umbilical separation.

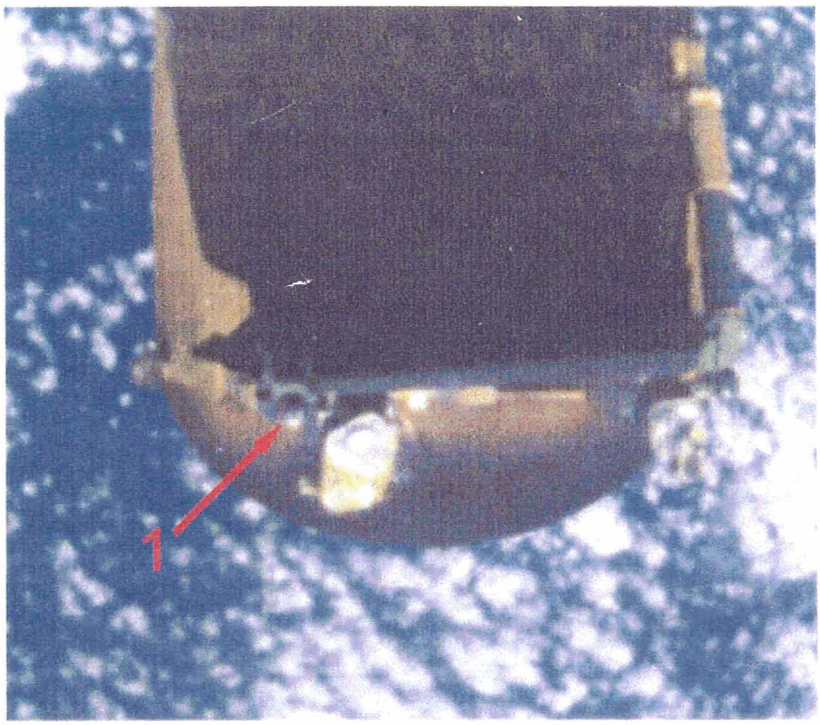

Figure 2.3.1. 16 mm Umbilical Well Camera View of Aft ET.

No anomalies were noted on the face of the LH2 umbilical after ET separation. The ET was in shadow for several seconds after separation, thus making detailed analysis of the ET at close

range difficult. However, some conditions were noted as the ET came into light. As typically seen on previous missions, frozen hydrogen was visible on the orifice of the LH2 17 inch connect. A large piece of debris (possibly frozen hydrogen) was seen moving aft of the ET and did not contact the ET. No anomalous conditions on the +Z side of the ET other than those seen at better resolution on the 35mm umbilical well film were noted. One special interest observation was noted on the 16mm umbilical well camera film: the separation bolt between the ET and the Orbiter at the aft end of the ET (EO-2 fitting) near the liquid hydrogen umbilical was confirmed not to be fully retracted. See Figure 2.3.1, annotation 1. Because of the limited resolution of the film, it could not be determined if the EO-2 bolt was "free-floating".

2.3.2 35mm Umbilical Well Camera Film

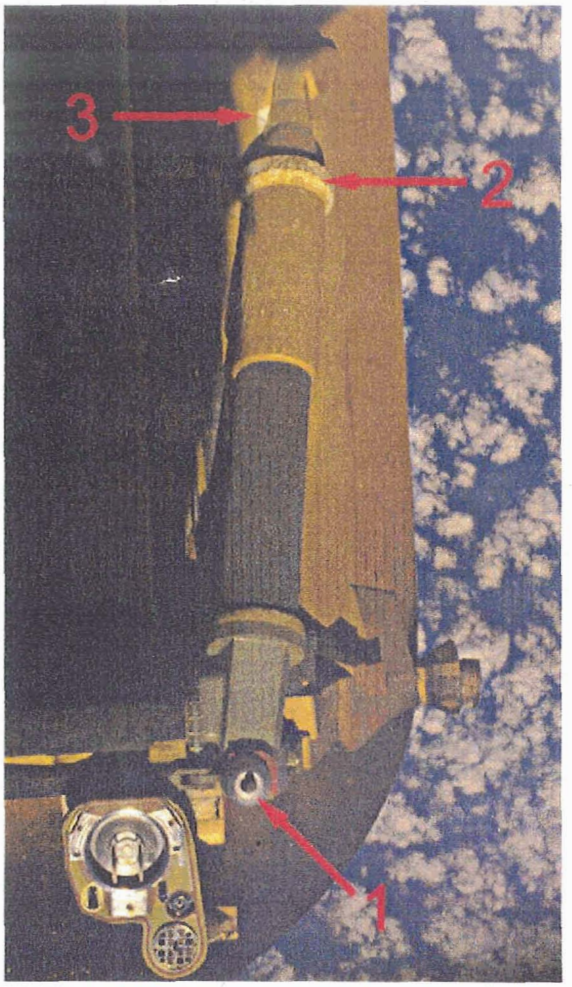

Figure 2.3.2 (A) 35mm Umbilical Well Camera View of Aft ET

The external tank appeared in excellent condition on the 35 mm umbilical well imagery of the STS-100 External Tank (ET-108). No anomalous conditions on the ET were noted. One special interest observation was noted:

The separation bolt between the ET and the Orbiter at the aft end of the ET (EO-3 fitting near the liquid oxygen umbilical) was confirmed not to be fully retracted as viewed from the umbilical film. See Figure 2.3.2 (A), annotation 1. Comparing successive frames, a lateral motion of the bolt was determined to have been present. The EO-3 bolt appeared similar to the protruded EO-3 bolt seen on the STS-106 and STS-102 umbilical well camera films. No attempt to measure the length of the STS-100 unretracted bolt was performed because of the bolt motion. An animated movie (gif image) showing the STS-100 bolt motion was created. The STS-100 bolt was clearly "free floating", and not rigid. A rigid bolt is a cause for concern since it could interfere with the proper separation between the ET and the Orbiter. Therefore, this event was not identified as an anomaly. (A Shuttle Program investigation of the STS-106 bolt extension was previously conducted in October, 2001.)

Minor TPS chipping and very small divots (typical of previous missions) were seen on the aft LO2 feedline flanges and on the aft bracket over the press lines. Small, shallow areas of TPS erosion and divoting were visible on the forward flange of the +Y ET/Orbiter thrust strut. See Figure 2.3.2 (A), annotation 2). Typical ablation and divoting of the TPS on the vertical section of the +Y electric cable tray adjacent to the LO2 umbilical were detected. Small "popcorn" divots were seen on the ET aft dome as well as along the LO2 feedline just forward of the Orbiter aft attach strut. A slightly larger area of TPS ablation was seen on the LH2 tank TPS near the forward end of the +Y thrust strut. See Figure 2.3.2 (A), annotation 3. The face of the LO2 umbilical carrier plate appeared to be in excellent condition (no indication of damaged or missing lightning contact strips was detected). The red-colored purge seal on the EO-3 ball joint fitting was in place during ET separation. On previous missions, detached or missing seals from the EO-3 ball joint fitting have been noted.

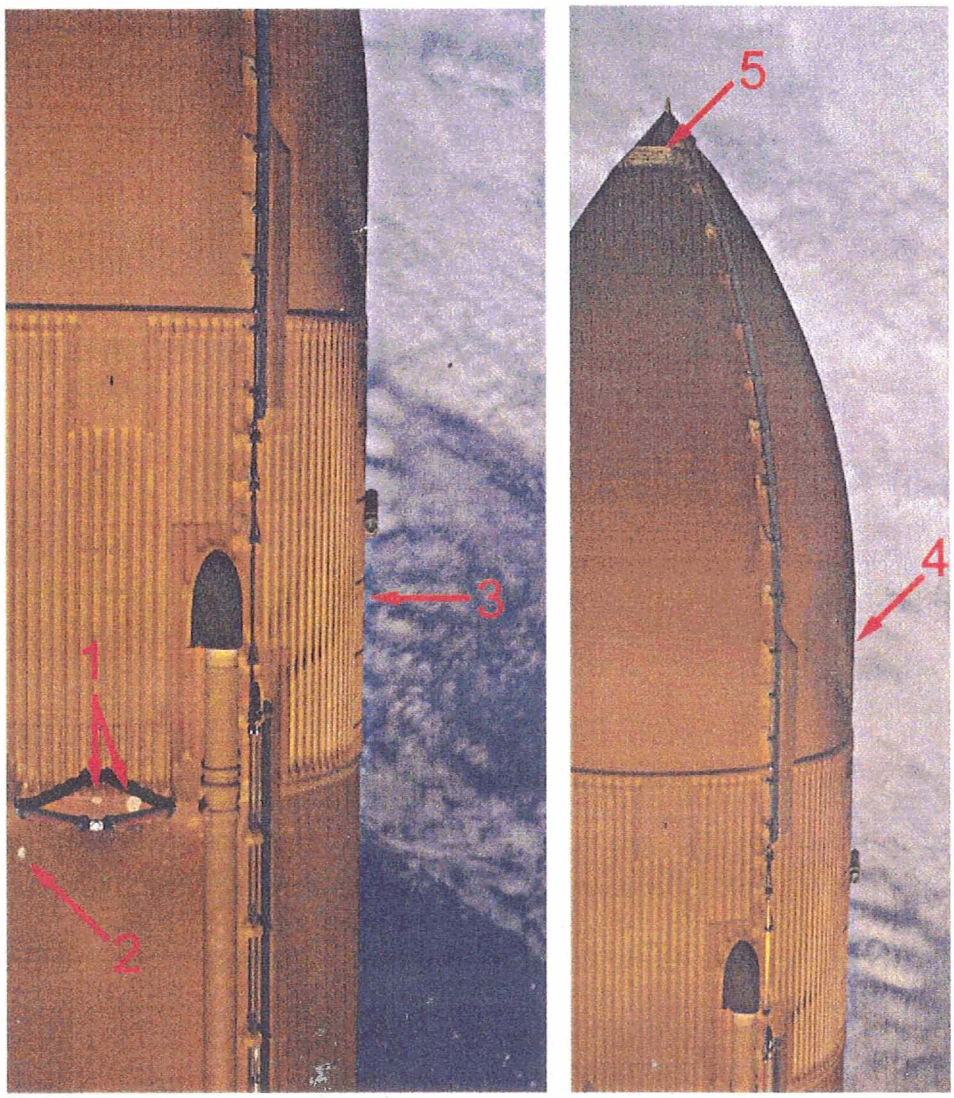

Figure 2.3.2 (B) 35mm Umbilical Well Camera View of Forward ET

Two slightly larger than normal areas of TPS ablation were seen under the forward bipod attach on the tank-to-intertank flange. See Figure 2.3.2 (B), annotation 1. Although these larger areas of TPS ablation and erosion are not normal, they have been seen on previous missions. One divot was visible on the LH2 tank TPS just aft of the –Y leg of the forward bipod. See Figure 2.3.2 (B), annotation 2.

The visible portion of the +Z/+Y ET Thrust Panel appeared in excellent condition and no divots were seen on the TPS between the +Y forward SRB attach and the LO2 feedline. See Figure 2.3.2 (B), annotation 3. The separation burn scar from the RSRB on the +Y ET TPS appeared normal. See Figure 2.3.2 (B), annotation 4. As expected, the left (-Y) SRB thrust panel was not imaged on this film.

The LH2 tank-to-intertank flange closeout appeared to be in excellent condition. With the exception of the divot mentioned previously under the Orbiter attach bipod, no other divots were seen on the tank-to-intertank flange closeout. No divots were seen on the intertank rib heads forward of the bipod or on the LH2 tank-to-intertank close-out flange in the +Y direction from the LO2 feedline.

The LO2 tank / Ojive TPS appeared to be in excellent condition. The nose of the ET appeared free of damage and the nose cap appeared in good condition. The aero friction and aero heating marks seen on the TPS just aft of the nose cone appeared similar to that typically seen on previous missions. See Figure 2.3.2 (B), annotation 5.

Notes: The 35mm umbilical well camera film (roll 411) was recorded from the Orbiter LO2 umbilical well. Sixty-six excellent quality frames imaging the ET were acquired. The +X translation maneuver was performed on STS-100 to facilitate the imaging of the ET with the umbilical well camera.

2.3.3 ET Handheld Photography

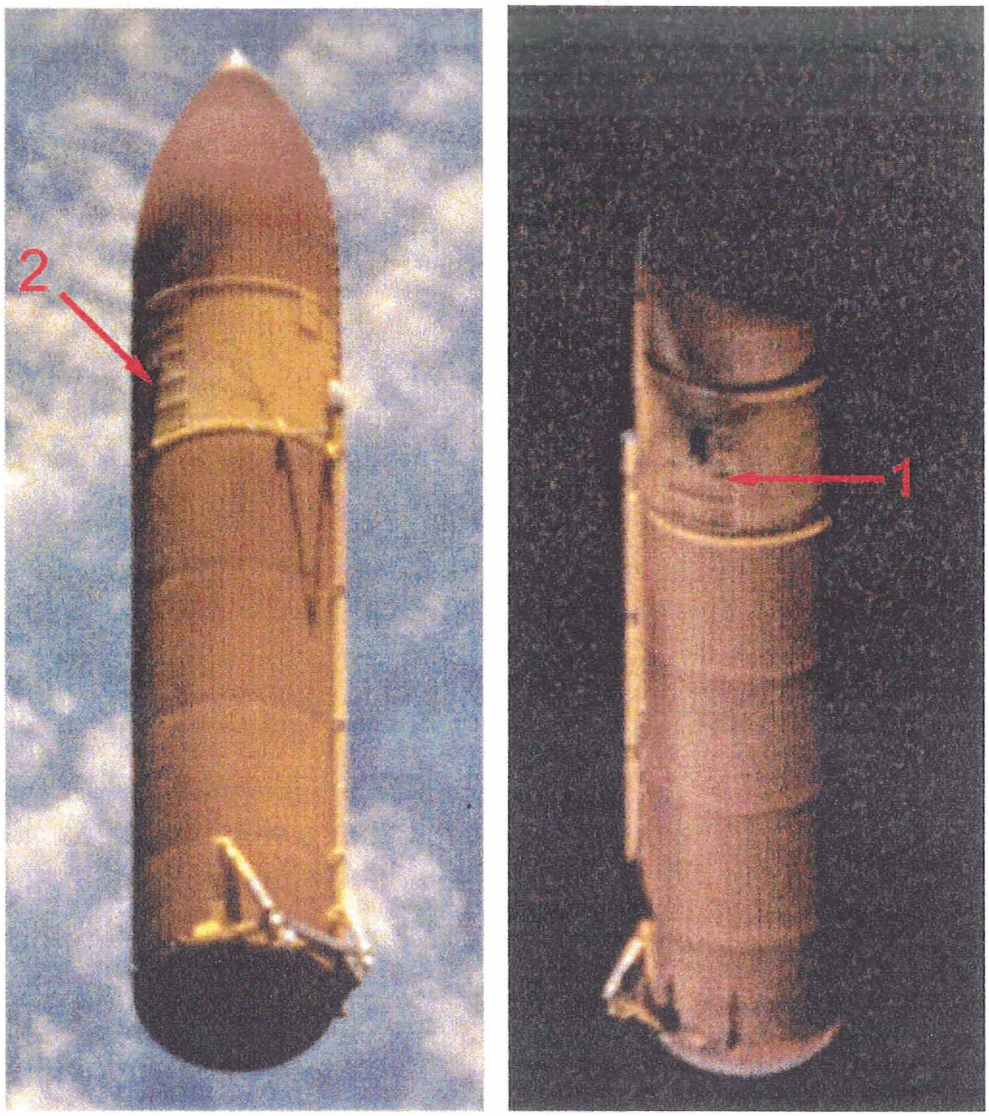

Figure 2.3.3 Crew Handheld Images of the External Tank

Thirty-six handheld pictures of the External Tank were acquired using the handheld 35mm Nikon F5 camera with a 400mm lens (roll 301). Timing data is present on the film with the first picture being taken at 16:56 (minutes : seconds) MET. The distance of the ET from the Orbiter at the time the first picture was taken was approximately 2.7 km. The astronauts performed a manual pitch maneuver from the heads-up position to bring the ET into view in the Orbiter overhead windows for the handheld photography.

Views of the nose, the aft dome, both limbs (+/- Y sides), the near side (+Z) and the far side (-Z) of the ET were obtained. The ET was fully illuminated with very little shadowing in most views. However, some of the views of the ET were in full shadow due to the angle of the ET relative to

the sun. The minimum resolvable object size from the ET imagery at a distance of 2.7 km was estimated to be approximately eight inches.

The normal SRB separation burn scars and aero-heating marks were noted on the intertank and nose TPS of the ET. The LO2 tank / Ojive TPS appeared to be in good condition.

The +Y ET thrust panel appeared in satisfactory condition. See Figure 2.3.3, annotation 1. No significant divoting of the thrust panel TPS was confirmed from the handheld imagery. The -Y thrust panel also appeared to be in good condition. See Figure 2.3.3, annotation 2. No divots were seen on the visible portion of the -Y thrust panel. No divots or unusual marks were seen on the LH2 tank TPS and the ET aft dome.

2.3.4 ET Handheld Video

The handheld video was excellent quality. Six minutes and forty-three seconds of video was recorded of the ET using the new PD-100 camcorder. No venting from the intertank gaseous hydrogen vent in the external tank was seen from the ET handheld video. The tumble rate of the ET as seen from the video was extremely slow and was estimated to have been 1.3 degrees per second. This rate is much lower than that seen on STS-102, STS-101, and STS-106. The astronauts performed a manual pitch maneuver from the heads-up position to bring the ET into view in the Orbiter overhead windows for the handheld video.

2.4 Landing Events Timing

The time codes from videos were used to identify specific events during the screening process. The landing event times are provided in Table 2.4.

STS-100 Landing and Drag Chute Event Times from Video:

Event Description	Time (UTC)	Camera
Main gear door opening	121:16:10:21.854	LRO-1
Left main gear tire touchdown	121:16:10:42.298	TV-1
Right main gear tire touchdown	121:16:10:42.398	TV-1
Drag chute initiation	121:16:10:44.934	TV-2
Pilot chute at full inflation	121:16:10:45.721	TV-1
Bag release	121:16:10:46.322	TV-1
Drag chute inflation in reefed configuration	121:16:10:47.256	TV-1
Drag chute inflation in disreefed configuration	121:16:10:50.793	TV-1
Nose gear tire touchdown	121:16:10:52.595	TV-1
Drag chute release	121:16:11:16.452	TV-1
Wheel Stop	121:16:11:33.258	PPOV

Table 2.4 Landing Event Times

2.5 Landing Sink Rate Analysis

Image data from the EL1036 35mm motion picture camera on runway 22 at Edwards Air Force Base was used to determine the landing sink rate for STS-100. This camera used a 100mm lens and was located on the north side of the runway. (This view is considerably different from the nominal camera view used to determine sink rate for landings at Kennedy Space Center, a view which is aimed straight down the runway.) The sink rates of the Orbiter main gear, nose gear, and a point midway between these two gear were measured over the final second prior to touchdown of the right main gear. Data points defining the top and bottom of the right main gear tires were collected on every frame (100 frames) along with points defining the bottom of the left main gear tires, the bottom of the nose gear tires, and a corresponding point on the runway directly below each gear. The distance from the top and bottom of the right main gear tire was used to determine a scaling factor. The height of each gear above the runway was calculated by the vertical difference between the bottom of the tires and the corresponding

ground point. An assumption was made that the line of sight of the camera was parallel to the horizon and that the error in picking the ground points on the runway was small.

Straight lines were fit to the data for the final one second, the final half-second, and the final quarter-second prior to touchdown of the right main gear. The slope of these lines defines the sink rate for each interval and the resulting values are listed in Table 2.5 below along with the associated uncertainties based on the line fits. Included in the sink rate data are the values calculated for the main gear midpoint. All of the sink rates are based on touchdown of the right main gear (excluding the left main gear) since the right main gear touched down first and, therefore, defined the end of the Orbiter sink rate. Figure 2.5 shows the main gear midpoint data points calculated over the 100 frame interval and the corresponding sink rate trends associated with each of the time intervals.

Time Prior to Touchdown	Main Gear Midpoint Sink Rate	Estimated Error (1σ)
1.00 Sec.	4.3 ft/sec	± 0.1 ft/sec
0.50 Sec.	4.3 ft/sec	± 0.1 ft/sec
0.25 Sec.	4.6 ft/sec	± 0.2 ft/sec

Table 2.5 Main Gear Midpoint Landing Sink Rate

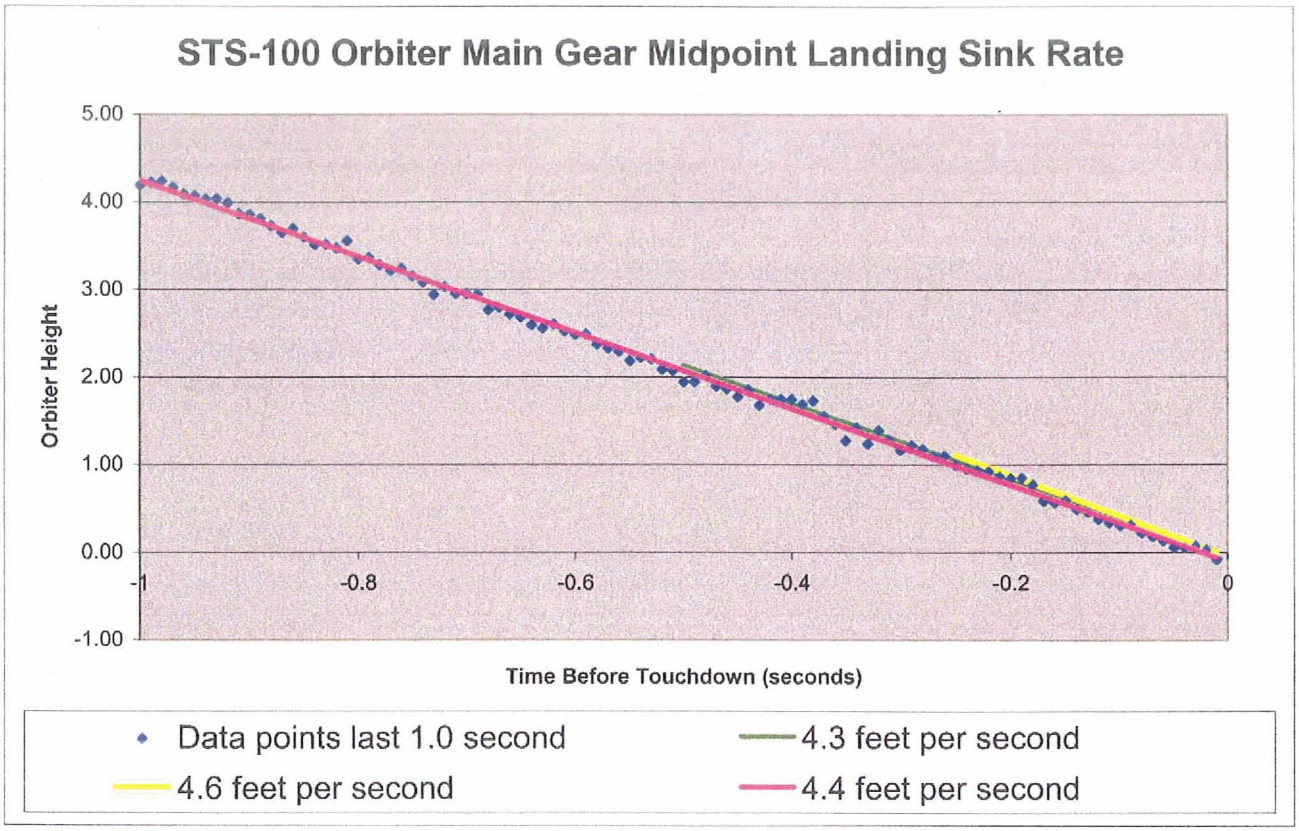

Figure 2.5 Main Gear Midpoint Landing Sink Rate

The maximum allowable main gear sink rate values are 9.6 feet / second for a 212,000 lb. vehicle and 6.0 feet/second for a 240,000 lb. vehicle. The landing weight of the STS-100 vehicle was reported to be 220,787 lbs.

2.6 Other

2.6.1 Normal Events

Normal events observed included:

- elevon motion prior to liftoff
- RCS paper debris from SSME ignition through liftoff
- ET twang
- ice and vapor from the LO2 and LH2 TSM T-0 umbilical prior to and / after disconnect
- multiple pieces of ET/Orbiter umbilical ice debris falling along the body flap during liftoff
- vapor off the SRB stiffener rings
- acoustic waves in the exhaust cloud during liftoff
- debris in the exhaust cloud (including water baffle material) after liftoff
- charring of the ET aft dome after liftoff
- ET aft dome outgassing
- roll maneuver
- linear optical effects
- recirculation
- SRB plume brightening
- SRB slag debris before, during, and after SRB separation

2.6.2 Normal Pad Events

Normal pad events observed included:

- hydrogen burn ignitor operation
- FSS and MLP deluge water activation
- sound suppression system water operation
- GH2 vent arm retraction
- TSM T-0 umbilical disconnect and retraction
- LH2 and LO2 TSM door closures

APPENDIX B. MSFC PHOTOGRAPHIC ANALYSIS SUMMARY

The MSFC Report can be accessed on their Engineering Photographic Analysis website at https://photo4.msfc.nasa.gov/.

Space Shuttle Mission STS-100

Engineering Photographic Analysis Summary Report
Marshall Space Flight Center

T. J. Rieckhoff (NASA/MSFC)
M. Covan (USA)
J.M. O'Farrell (USA)

May 23, 2001
Marshall Space Flight Center,
Huntsville, AL 35812

Contents

Figures

Engineering Photographic Analysis Report for STS-100

Launch of the one-hundred-fourth Space Shuttle mission, STS-100, the sixteenth flight of the Orbiter Endeavour (OV-105), occurred April 19, 2001 at approximately 1:41 PM CDT, from launch complex 39A, Kennedy Space Center (KSC), Florida. Launch time was reported as 01:109:18:40:41.998 Universal Coordinated Time (UTC) by the MSFC Flight Evaluation Team.

STS-100 Photographic Analysis Summary:

Out-of-family conditions, a pulsing motion of the TPS on both the left and right Orbiter stinger pods, were observed on this mission from cameras E-17 and E-18. Other significant observations were both the EO-3 and EO-2 separation bolts observed to be protruding from their respective fitting bores, as observed from Umbilical Well cameras.

During post-flight inspection unburned propellant was discovered in one of the motors of the right SRB forward BSM cluster. A review of BSM plumes at separation from recent missions was done to compare motor performance, duration, and plume shape.

Further details on these events and their respective analyses are provided in the "Observations" section of this report. Movies listed below are provided on the website.

1. STS-100 Right OMS TPS Motion
2. STS-100 Left OMS TPS Motion
3. Comparison of Right SRB BSM Firing at Separation from Recent Missions
4. STS-100 Left SRB Aft Upper Attach at Separation

Photographic Analysis Website:

Further information concerning photographic analysis of this and previous space shuttle missions is available on the MSFC Engineering Photographic Analysis website at URL:

http://photo4.msfc.nasa.gov/STS/sts100/sts100.html

Information available on the MSFC Engineering Photographic Analysis website includes:

- Photographic Acquisition Disposition Document (PADD),
- Individual camera status and assessments,
- Annotated images of notable observations,
- Movies of select events, and
- Photographic Analysis Mission Summary Report (PDF format).

Photographic Coverage:

Photographic and video coverage has been evaluated to determine proper operation of the flight hardware. Video and high-speed film cameras providing this coverage are located on the fixed service structure (FSS), mobile launch platform (MLP), perimeter sites, Eastern Test Range tracking sites and onboard the vehicle.

Sixty-six engineering photographic products consisting of launch video, ground-based engineering films and onboard film were received and reviewed at MSFC. Camera coverage received at MSFC for STS-100 is illustrated in the following table.

	16mm	35mm	Video
MLP	18		4
FSS	5	0	3
Perimeter	0	7	6
Tracking	0	8	10
Onboard	2	2	1
Other	0	0	0
Totals	25	17	24

Due to the atmospheric haze, many tracking video and film products had soft focus. Also, camera focus is soft on camera E7. Film cameras E220 and E213 momentarily loses track of the vehicle in the clouds. Clouds obscure view of vehicle early in ascent on video camera TV13. Film camera E54 viewed the lower half of the vehicle and not the upper half as programmed. Film from camera FL101 unexpectedly ends shortly after ET separation. At liftoff, exposure of video from OTV041 becomes too dark to observe detail on vehicle.

T-Zero Times :

T-Zero times are regularly determined from MLP cameras that view the SRB Holddown posts, without doghouse covers, M-1, M-2, M-5, and M-6. These cameras, listed below with their corresponding Holddown Post, record the observation times of explosive bolt combustion products.

Holddown Post	Camera	Time (UTC)
M-1	E9	109:18:40:41.995
M-2	E8	109:18:40:41.996
M-5	E12	109:18:40:41.996
M-6	E13	109:18:40:41.998

SRB Separation Timing:

SRB separation time, as recorded by observations of the BSM combustion products from long-range film camera E207, occurred at 109:18:42:45.440 UTC.

Anomalies:

All observations in this report have been forwarded to the appropriate office for proper disposition.

Observations:

Video Camera OTV-070: Free Hydrogen Burning

Free Hydrogen burning was observed near the vertical stabilizer at SSME ignition. This particular phenomenon is a typical occurrence during SSME ignition and appears to be within normal limits.

Also noted was motion of the Orbiter Aft Bulkhead between the three SSMEs. This motion has been observed and reported on prior missions.

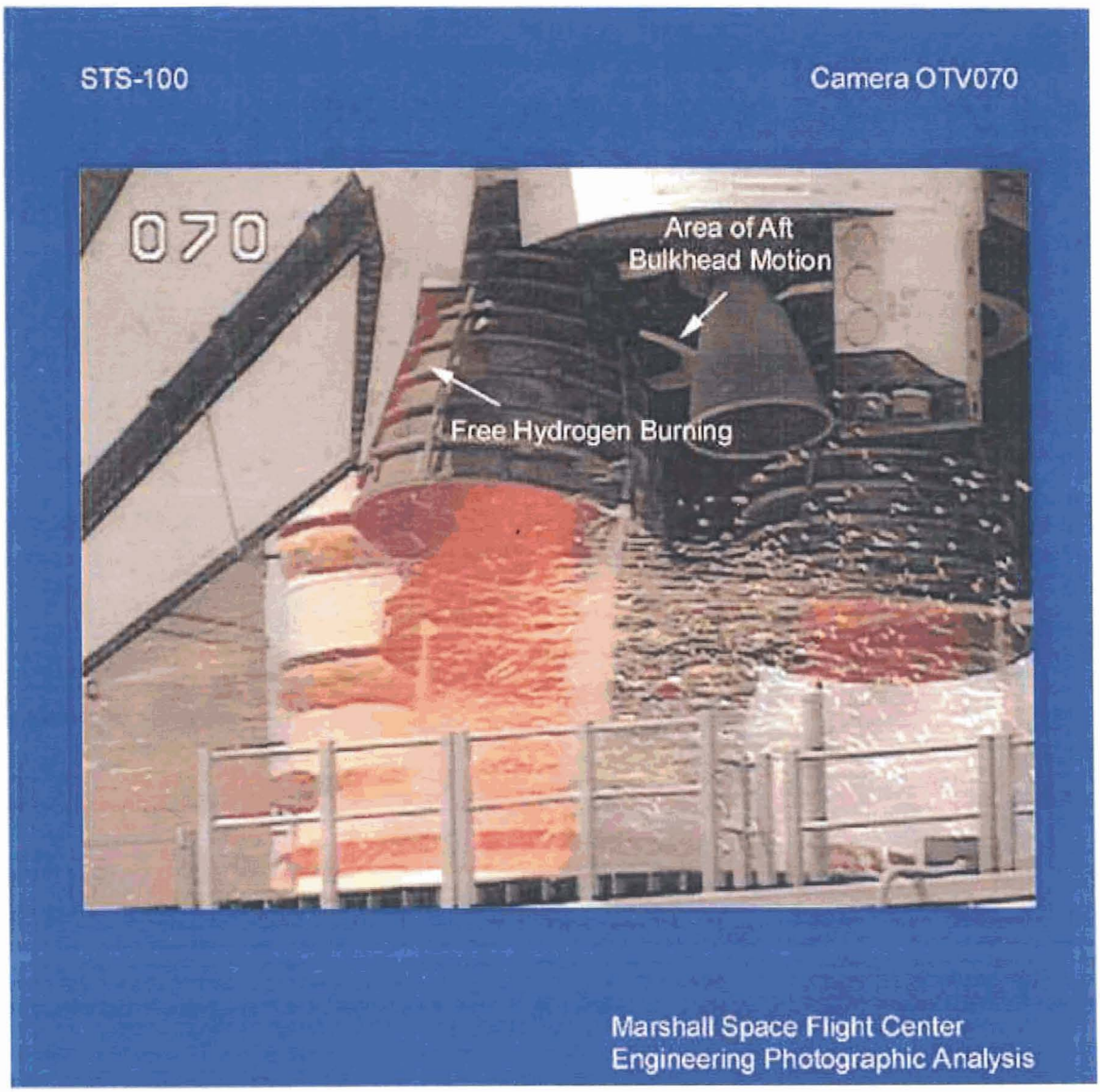

Figure 1. Free Hydrogen Burning

Film Camera E14: Leaking Sound Suppression System

Water leaking from the sound suppression system near Holddown Post M8 was observed.

Figure 2. Leaking Water from Sound Suppression System

Video Camera OTV-063: Ice/Frost Impacts LH2 Recirculation Line

Ice/frost from the 17 inch LH2 Disconnect was observed to strike the LH2 recirculation line. No damage was noted.

Figure 3. Ice/Frost Impacts LH2 Recirculation Line

Film Camera E34: Ice/Frost Falls Between the Orbiter and ET

A number of ice/frost debris objects, apparently from the LOX Feedline on the ET, fall between the Orbiter and the ET. No impacts were observable and no damage was noted.

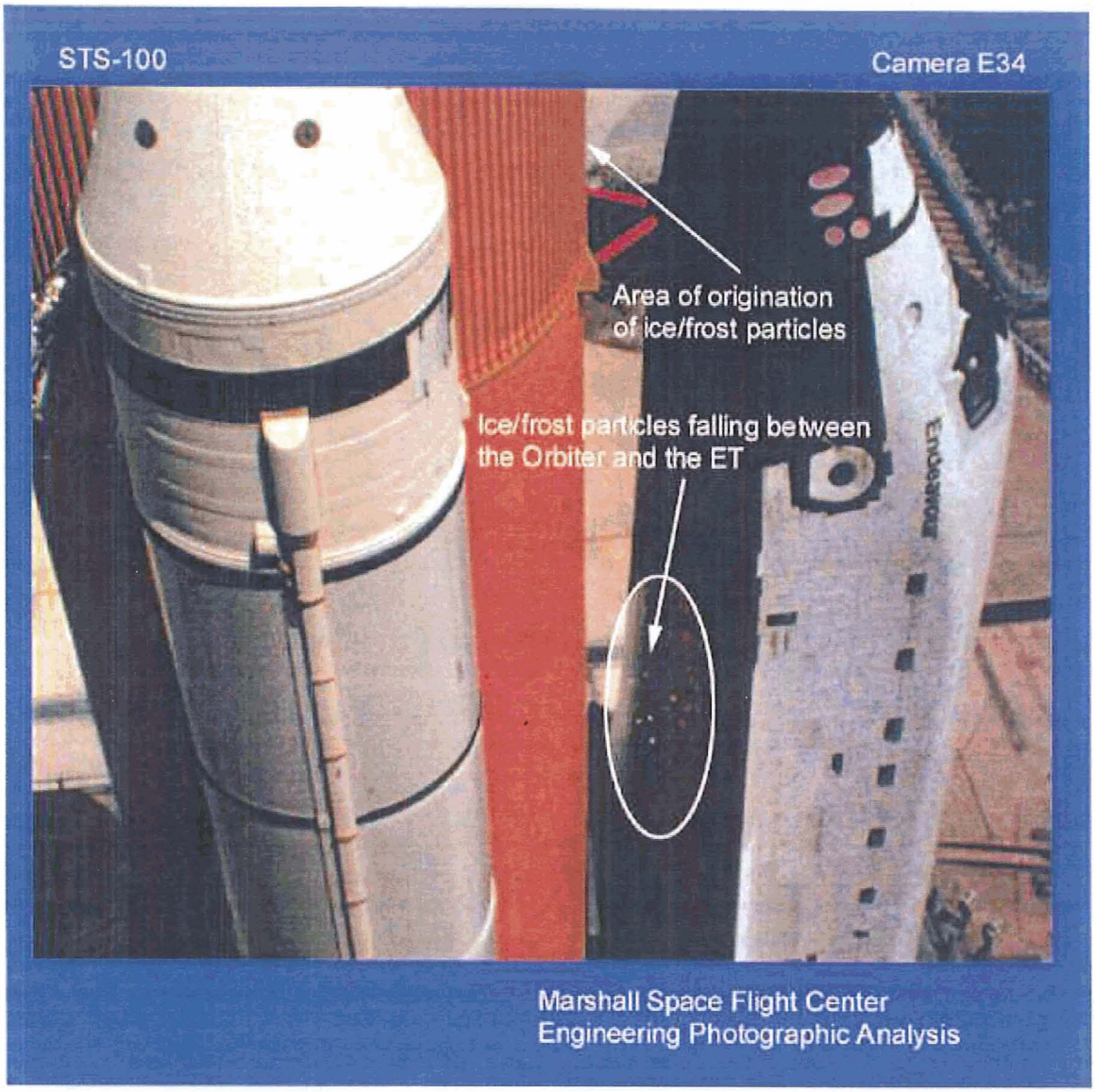

Figure 4. Ice/Frost Falls between the Orbiter and ET

Video Camera OTV-061: Ice/Frost Falls Between Orbiter and ET

A small piece of ice or frost, apparently originating from the LOX Feedline forward of the ET-Orbiter attach bipod, was noted falling between the Orbiter and the ET. No impact with the ET or Orbiter could be discerned.

Figure 5. Ice/Frost Falls Between Orbiter and ET

Film Camera E18: Motion of TPS on Left Stinger Pod

A pronounced pulsing and rippling motion of the TPS on the bottom panel of the Left Stinger Pod was observed, starting at 109:18:40:38.386 UTC and lasting for approximately 0.5 seconds during SSME startup.

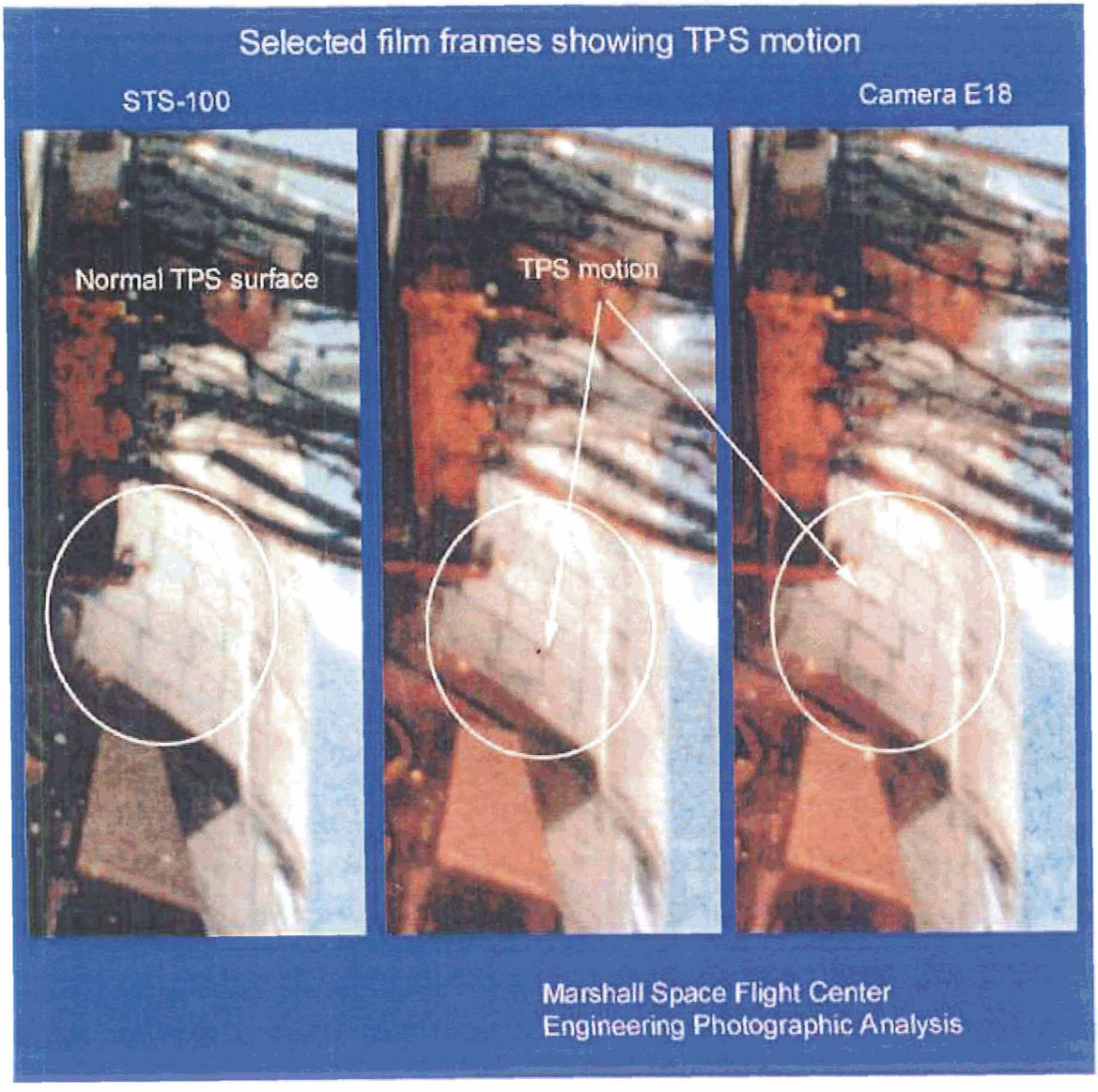

Figure 6. Motion of TPS on Left Stinger Pod

Film Camera E17: Motion of TPS on Right Stinger Pod

The pulsing and rippling motion of the TPS on the bottom panel of the Right Stinger Pod was also observed, starting at about 109:18:40:38.4 UTC and lasting for approximately 0.3 seconds during SSME startup.

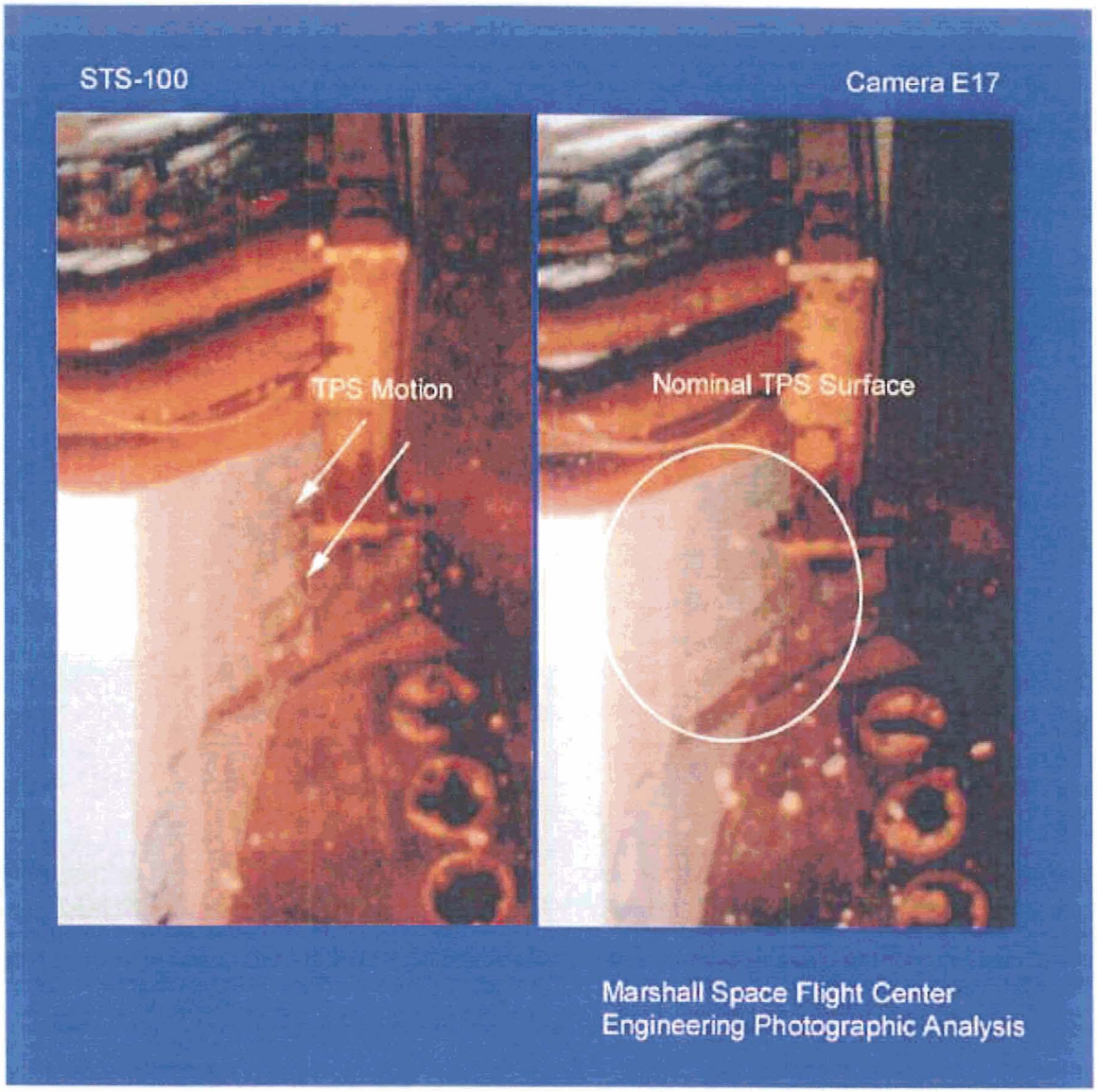

Figure 7. Motion of TPS on Right Stinger Pod

Film Camera E13: Liquid Observed at Holddown Post M6 Housing

Liquid was observed leaking from the Holddown Post M6 housing after PIC Firing. The image of the flowing liquid in Figure 8 was taken just after liftoff.

Figure 8. Liquid Observed at Holddown Post M6 Housing

Film Camera E12: SRB Foot near Holddown Post M5

A photograph of Holddown Post M5 was made just after liftoff to view the condition of the SRB Foot. Post-flight inspection revealed a darkened area on the underside area near the bore. This darkened area was thought to be caused by some material which had burned on the SRB foot. The darkened area described was not evident on the SRB Foot just after liftoff, as shown in Figure 9.

Figure 9. SRB Foot near Holddown Post M5

Film Camera E17: Engine Streak in SSME#3 Plume

A green-colored engine streak in SSME#3 plume was noted on film from Camera E17 at 109:18:40:43.624 UTC. A faint greenish-yellow line may be observed extending from the upper tip of the green-colored streak to the edge of the nozzle.

Figure 10. Green-colored Engine Streak in SSME#3 Plume

Video Camera ET-207: Debris Falling Aft of Orbiter

A notable debris object was observed falling aft of the Orbiter during ascent.

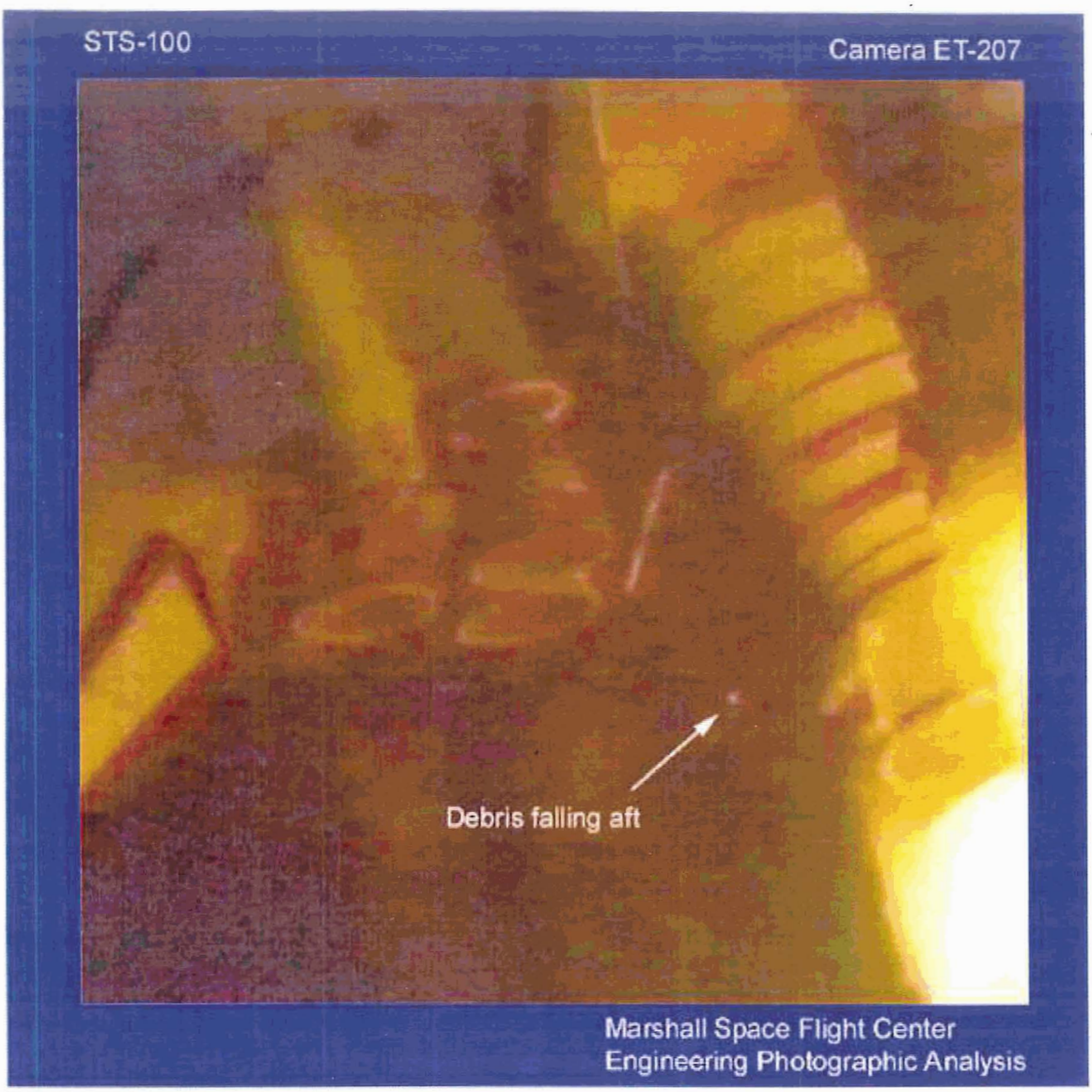

Figure 11. Debris Falling Aft of Orbiter

Video Camera ET-207: Streak in SSME Plumes

Several debris induced streaks, and possibly engine streaks, in the SSME plumes were noted during ascent. Figure 12 illustrates one such event.

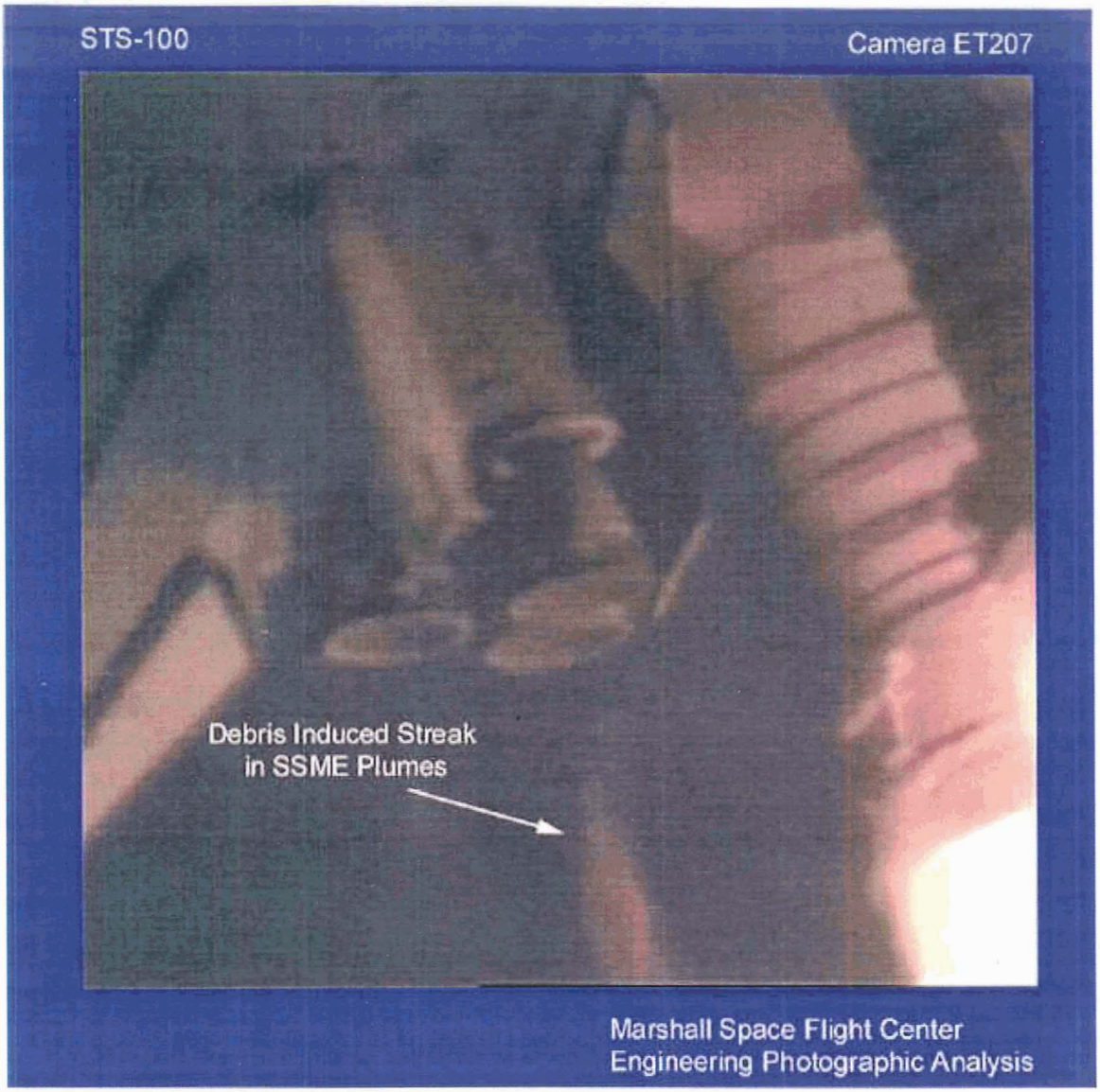

Figure 12. Debris Induced Streak in SSME Plumes

Video Camera TV4A: Debris Induced Streak in SSME Plumes

A debris induced streak in the SSME plumes was noted on Video Camera TV-4A.

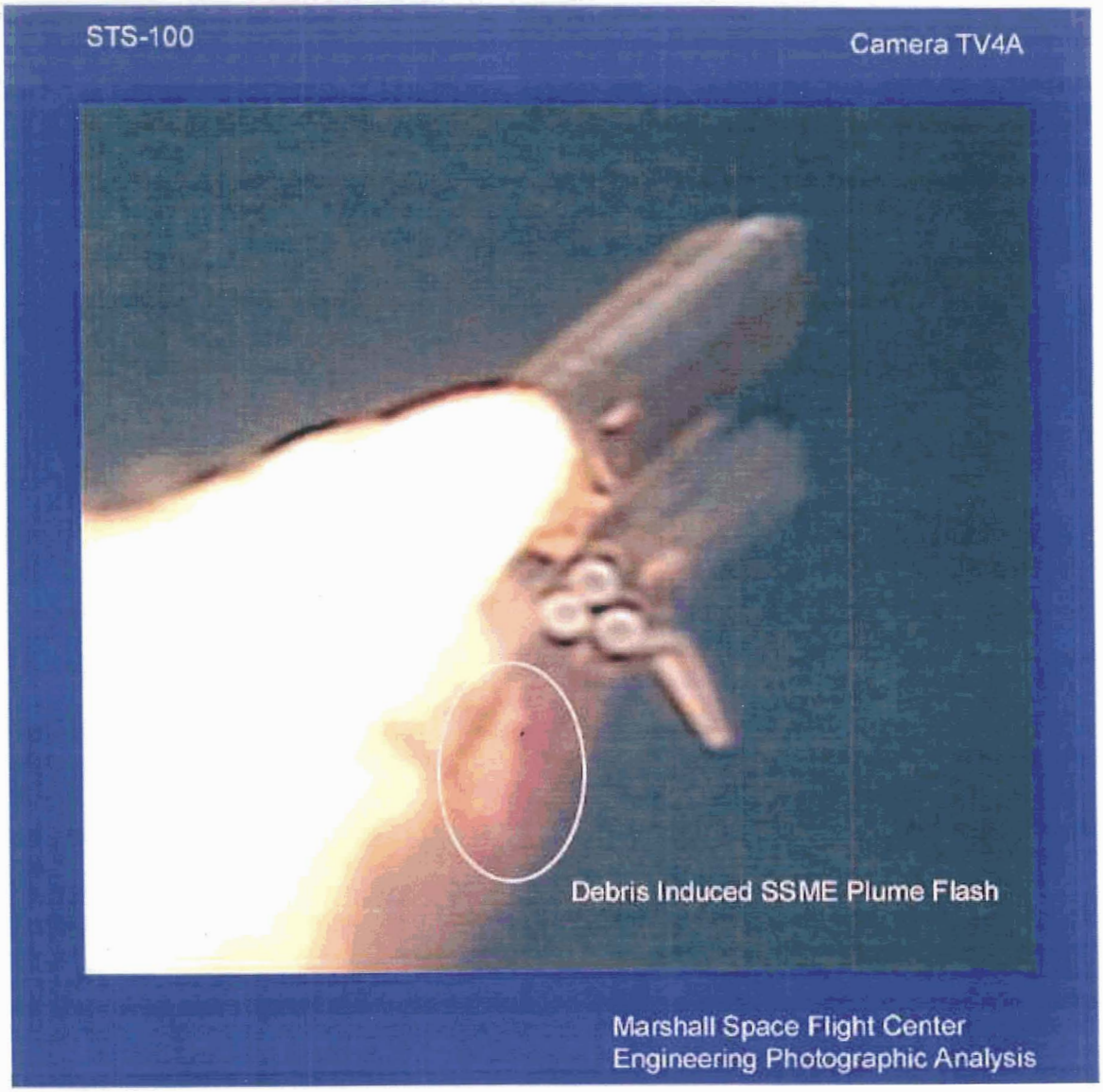

Figure 13. Debris Induced Streak in SSME Plumes

Film Camera E207: Dark Area in BSM Plume

A dark area was observed in the Right SRB BSM Plume. It was thought this dark area might be attributable to one of the BSM motors that did not completely burn all its propellant, Figure 16. A review of BSM operation at separation for recent missions was performed to address this possibility, Figure 15.

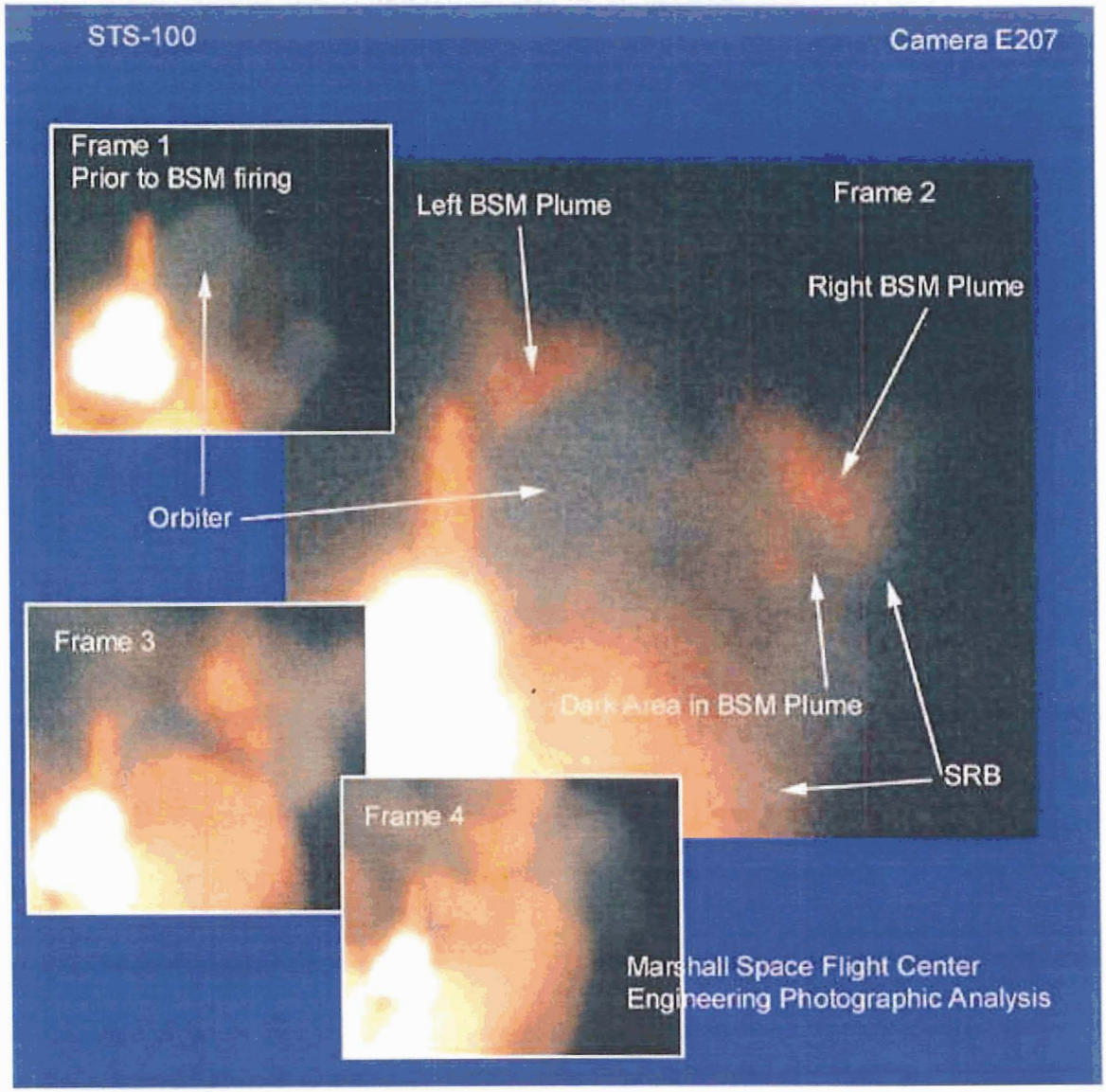

Figure 14. Dark Area in BSM Plume

Film Camera E207: BSM Plume Comparison

A comparison of the BSM Plume structure from several recent missions was made. No significant differences in plume performance or shape could be discerned. The dark area observed on mission STS-100 in the BSM Plume was visible in the BSM Plumes on mission STS-98, but was not visible on the other missions. Results of this visual study indicate that the dark area in the BSM plumes is probably not attributable to BSM flameout and the dark area is more likely caused by shadows or camera angle.

Figure 15. Comparison of BSM Plumes for Several Recent Missions

Film Camera E207: BSM Firing Duration Comparison

A movie of BSM motors firing after separation was made to compare firing duration from STS-100 and three recent missions. It was found that the duration of the BSM firing was approximately the same on the three missions STS-100, STS-106, and STS98. The trajectory of STS-97 was different than the other three missions and booster motor plumes obscured the completion of its BSM firing.

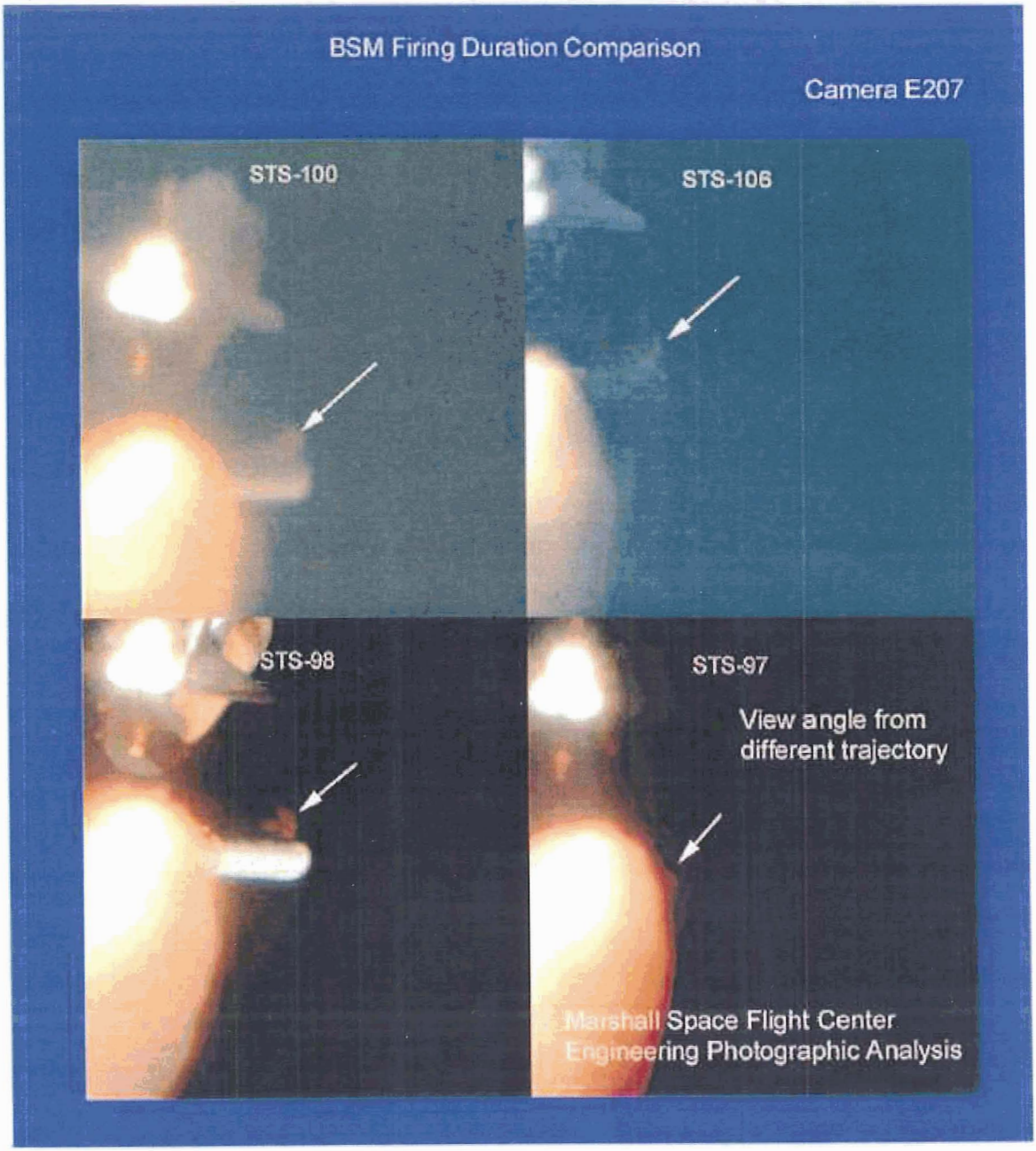

Figure 16. BSM Firing Duration Comparison

USA SRB Photo: BSM Photograph

A photograph of the Right Booster BSM made during post-flight inspection shows the remaining propellant. It was thought that this unburned propellant might have resulted in some visible difference in the BSM plumes.

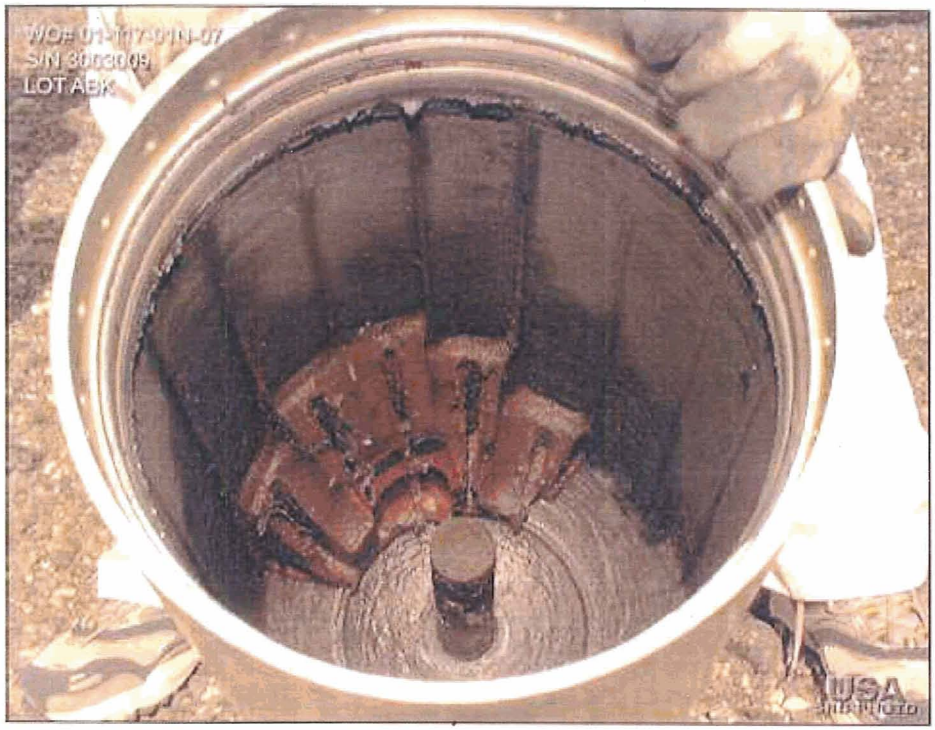

Figure 17. Photograph of Recovered BSM with Remaining Propellant

16 mm Umbilical Well Film Camera FL102: Tape-like Strand at Separation

A long tape-like strand noted before and after separation. Although not imaged below, the strand extended past the fiducial mark on the film in later frames.

Figure 18. Tape-like Strand at Separation

35mm Umbilical Well Camera: Protruding EO-3 Bolt

The EO-3 separation bolt was observed protruding on this mission. Divoting/popcorning on the Aft Dome appeared nominal.

Figure 19. Protruding EO-3 Bolt

16mm Umbilical Well Film Camera FL102: Protruding EO-2 Separation Bolt

A shadow from the EO-2 separation bolt was observed, indicating that the bolt was protruding. The shadow cast is similar to the shadow from the protruding EO-3 separation bolt.

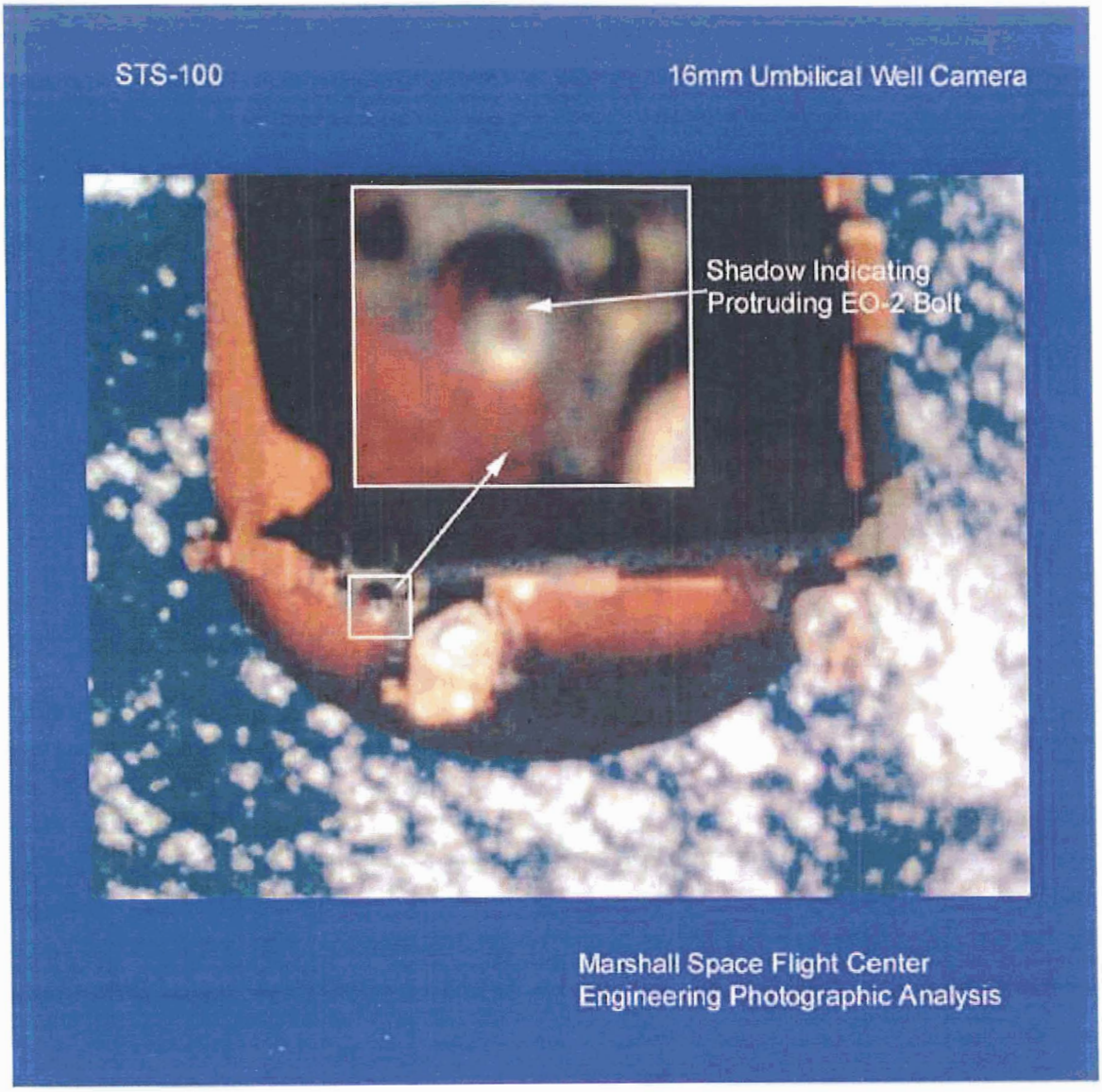

Figure 20. Protruding EO-2 Separation Bolt

35mm Umbilical Well Camera: ET Nosecap and Right SRB Thrust Panel

Close up views of the ET nosecap and the right SRB thrust panel. Both structures appeared normal with no notable divoting.

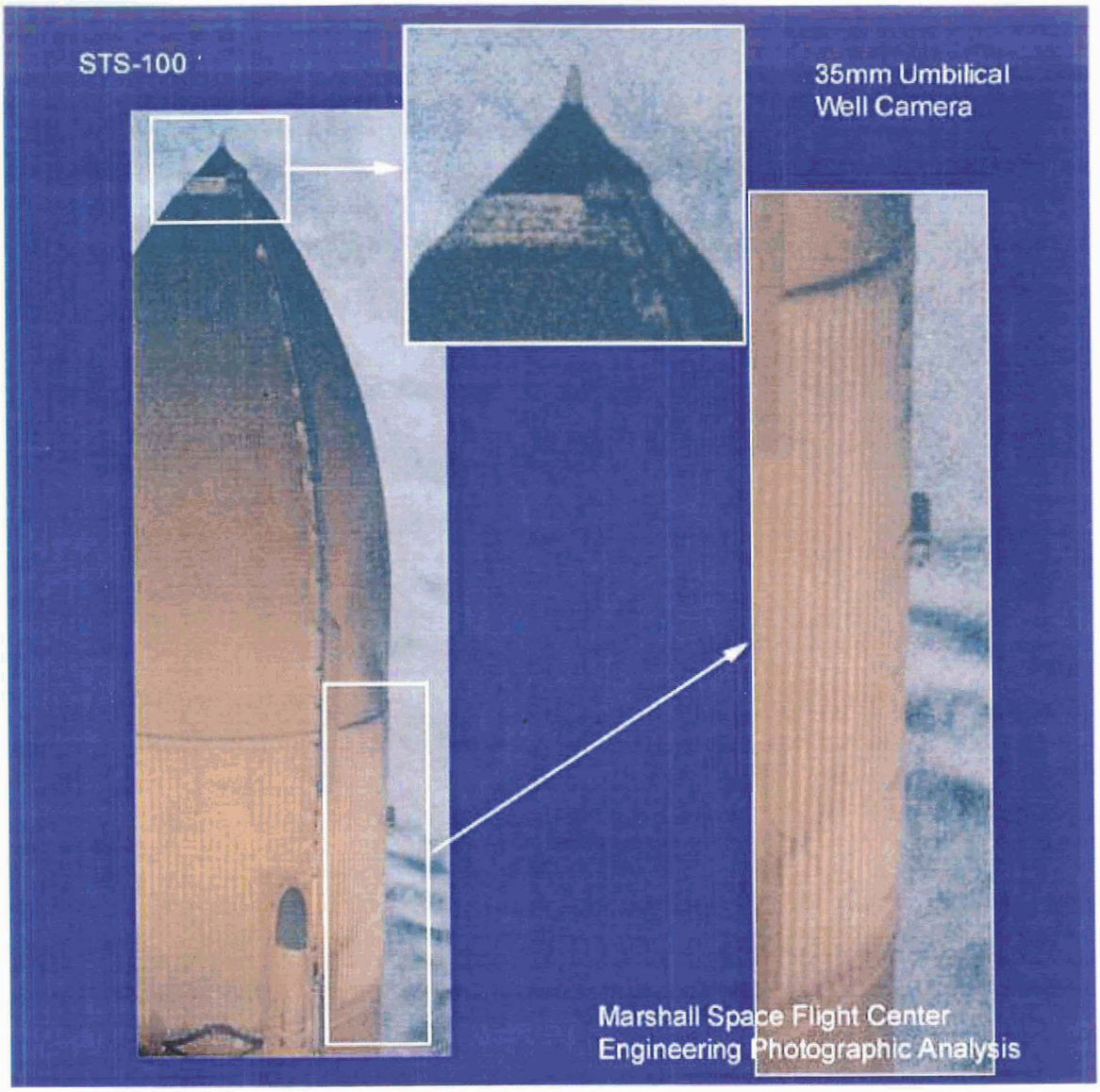

Figure 21. Close View of ET Nosecap and Right SRB Thrust Panel

35mm Umbilical Well Film Camera: Divoting at ET/Orbiter Forward Attach Bipod

Several TPS divots were noted near the ET/Orbiter Forward Attach Bipod. Two divots directly beneath the bipod and one just aft and right of the bipod were observed.

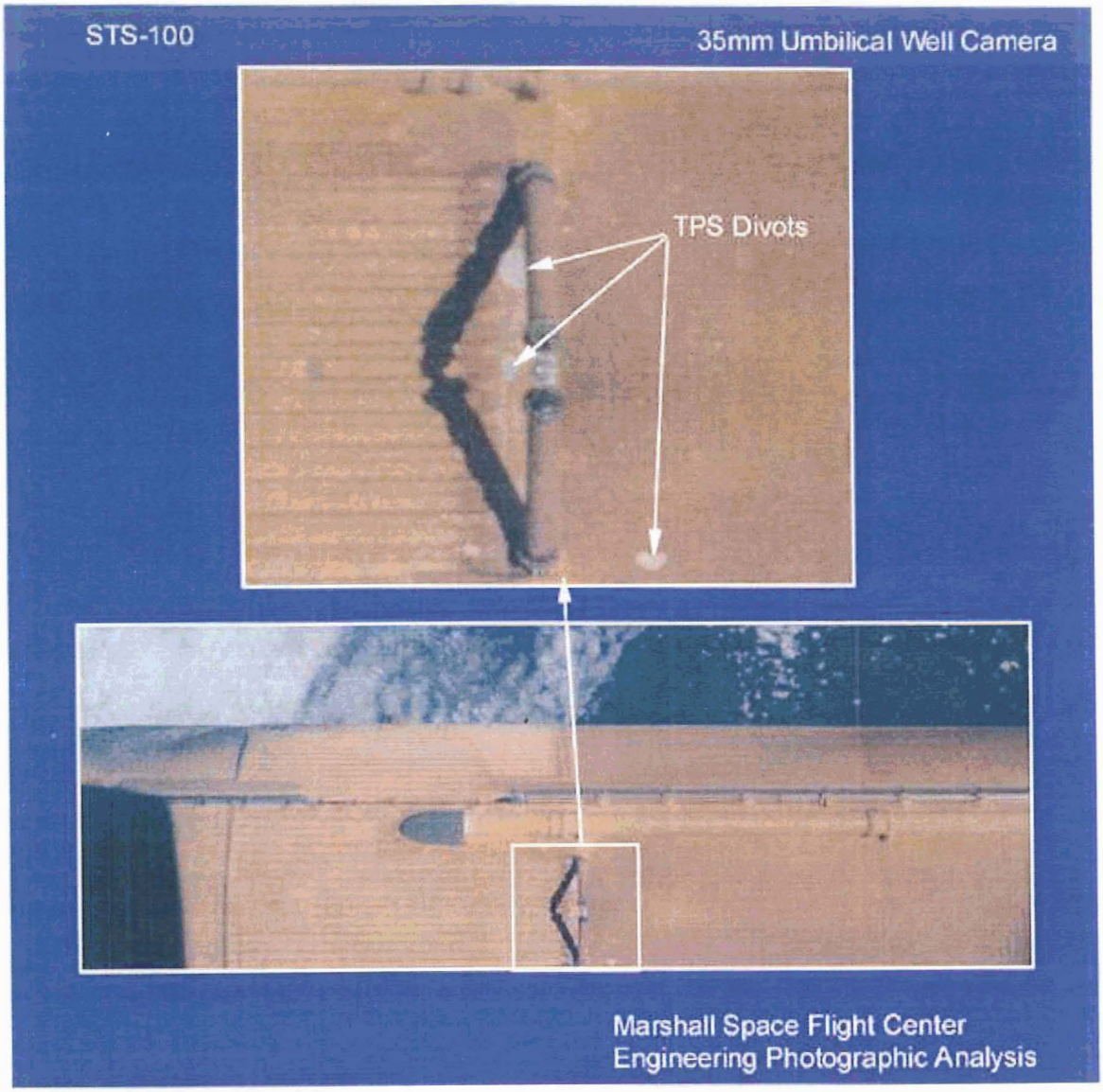

Figure 22. ET TPS Divoting near the Bipod

16mm Umbilical Well Film Camera FL102: ET TPS Divoting

Divots were observed in the vicinity of the LH2 tank to Intertank flange.

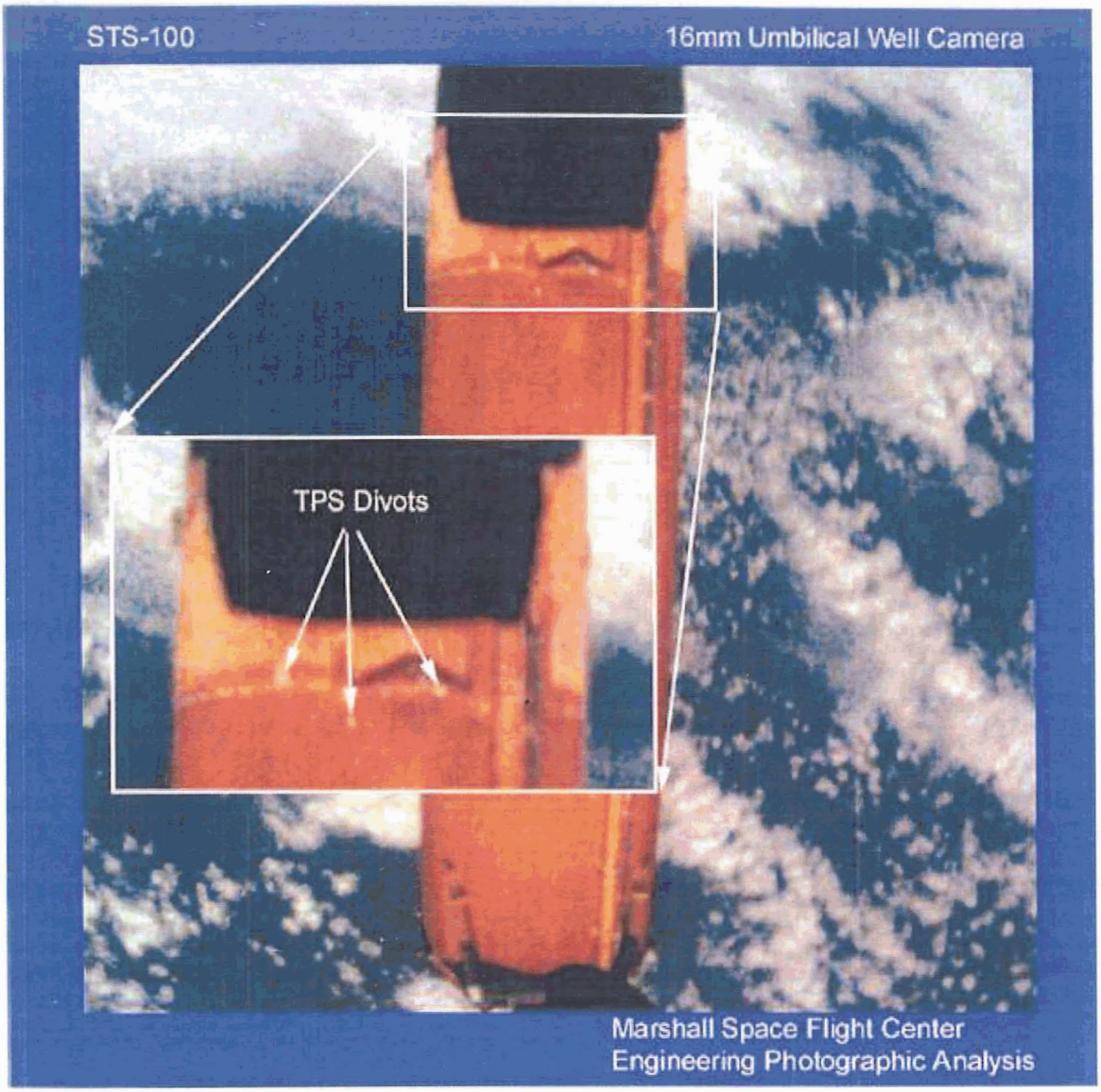

Figure 23. ET TPS Divoting

Astronaut Handheld 35mm Camera: -Z View of External Tank

No damage to the –Z side of the External Tank was observed at the resolution of this image.

Figure 24. –Z View of External Tank

Astronaut Handheld 35mm Camera: -Y and +Z View of External Tank

The BSM burn scars are visible on the -Y side of the External Tank. No damage to the External Tank was observed at the resolution of this image.

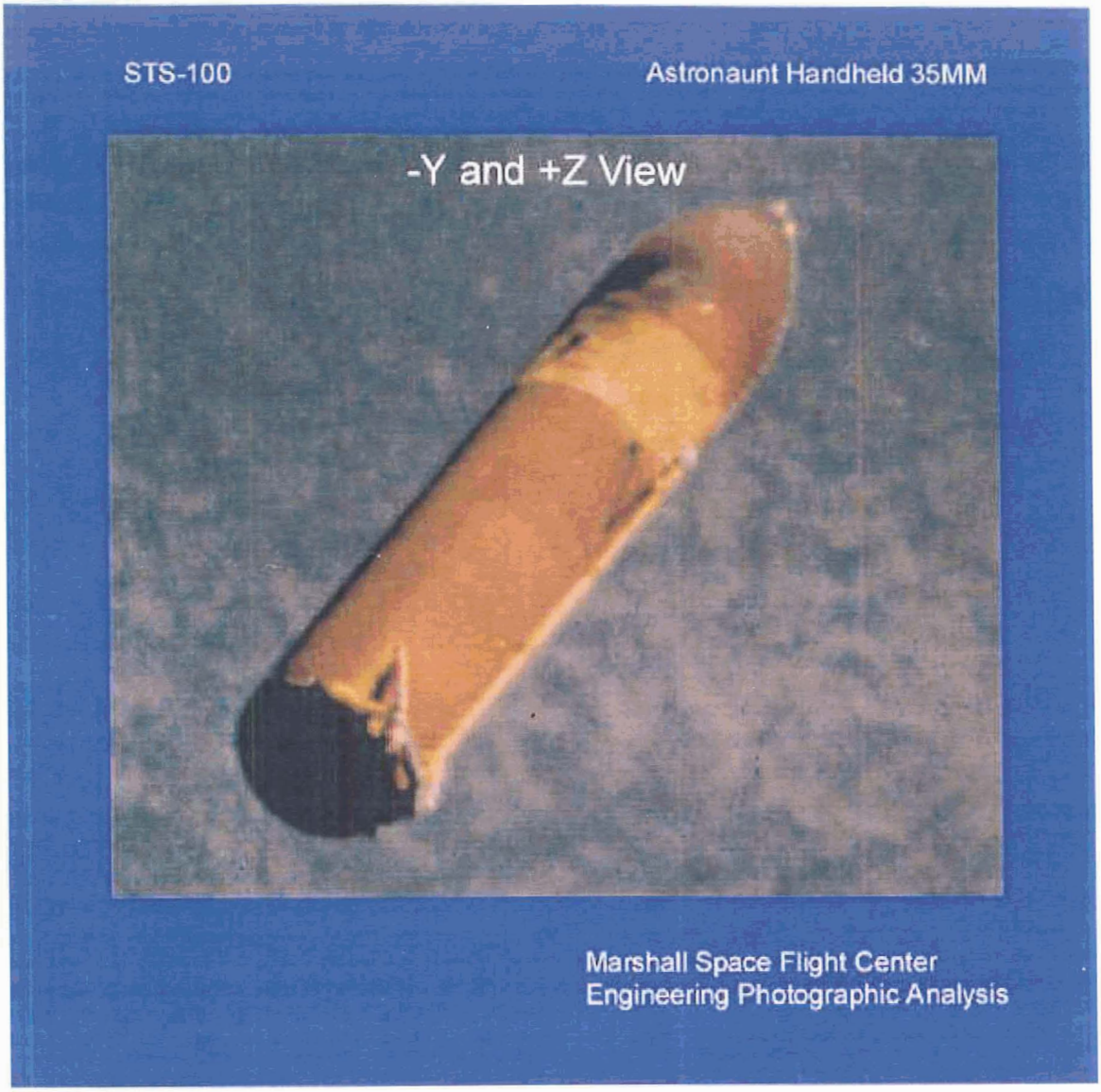

Figure 25. –Y and +Z View of External Tank

Astronaut Handheld 35mm Camera: +Y View of External Tank

The BSM burn scars are visible on the +Y side of the External Tank. No damage to the External Tank was observed at the resolution of this image.

Figure 26. +Y View of External Tank

Individual Camera Assessments:

Assessments for individual cameras are listed below. The assessments for all individual cameras including camera characteristics as noted in the Photographic Acquisition Disposition Document (PADD) for flight STS-100 may also be found on the website.

Video Camera Assessments

TV13 - Clouds obscure vehicle early in ascent.
TV4A - Both engine and debris induced streaks noted in SSME plumes.
OTV009 - Pad debris noted rising and falling. Typical ice/frost from LH2 disconnect. Ice strikes umbilical well sill. No damage noted. Typical wing motion at liftoff. Ice noted on SSME#2 eyelid.
OTV041 - At liftoff, exposure becomes too dark to observe detail on vehicle.
OTV051 - Mach diamond formation in 3-2-1 order. Free burning Hydrogen observed near vertical stabilizer.
OTV054 - Typical wing motion at SSME ignition and liftoff. Typical ice/frost from 17 inch disconnects.
OTV061 - Ice/frost noted falling between ET and Orbiter near the ET intertank. No impact was observed.
OTV063 - Ice from 17 inch disconnect impacts recirculation Line. No damage noted.
OTV070 - Free burning Hydrogen observed. Motion of Orbiter Aft Bulkhead observed during SSME startup.
ET207 - Typical debris observed falling aft of vehicle. Glowing debris particles ejected from SRB plume prior to, during and after separation. Debris-induced streaks observed in SSME plume. Linear optical distortions noted. Flow recirculation noted. Body flap motion noted. Focus was soft.
ET212 - Glowing debris particles ejected from SRB plume after separation.
ET213 - Free burning Hydrogen near vertical stabilizer noted at SSME ignition. This event appears to be within family of our previous experience base.
OB1 - Image size of the ET was too small and sometimes too dark to resolve much detail in TPS condition.

Film Camera Assessments

E1 - Pad debris noted rising and falling.
E3 - Typical debris observed falling aft of vehicle.
E4 - Pad debris noted rising and falling. Typical ice/frost from 17-inch disconnects.
E6 - Typical ice/frost from 17-inch disconnects. Ice/frost noted falling from ET/Orbiter vertical strut.
E7 - Pad debris noted rising and falling. Camera focus is soft.
E8 - SRB Holddown Post M2 PIC firing time at 18:40:41.996 UTC. Motion of Holddown Post Shoe observed at PIC firing.
E9 - SRB Holddown Post M3 PIC firing time at 18:40:41.995 UTC.
E10 - Pad debris noted rising and falling.
E11 - Pad debris noted rising and falling.
E12 - SRB Holddown Post M5 PIC firing time at 18:40:41.996 UTC.
E13 - SRB Holddown Post M6 PIC firing time at 18:40:41.998 UTC. Motion of Holddown Post Shoe observed at PIC firing.
E14 - Pad debris noted rising and falling. Leaking sound suppression water pipe to left of frame out of field of view.
E16 - Pad debris noted rising and falling. Typical ice/frost from 17-inch disconnects.
E17 - Typical ice/frost from LO2 T-0 umbilical. Motion of TPS on Right Stinger Pod observed, starting around 40:38.4 UTC for approximately 0.3 seconds. Green colored engine streak observed in SSME#3 plume at 18:40:43.624 UTC. Motion of SSME#2 eyelid blanket observed at 18:40:38.6 UTC.
E18 - Typical ice/frost from 17-inch disconnects. Typical ice/frost from LH2 T-0 umbilical. Pronounced TPS motion observed on bottom panel of Left Stinger Pod, starting at 109:18:40:38.386 UTC for approximately 0.5 seconds.

E19 - Typical ice/frost from 17-inch disconnects. Mach diamond formation in 3-2-1 order.

E20 - Typical ice/frost from 17-inch disconnects. Ice noted on SSME#2 eyelid. Mach diamond formation in 3-2-1 order. Tile chips on Stinger Pod noted. Water baggy material debris observed.

E31 - Pad debris noted rising and falling. Typical ice/frost from LH2 disconnect. Typical wing motion noted. Ice on SSME#2 eyelid.

E33 - Frost noted around GUCA.

E34 - Typical debris observed falling aft of vehicle. Multiple pieces of ice, apparently from the LOX Feedline forward of the ET-Orbiter attach bipod, fall between the Orbiter and the ET. No impact with Orbiter noted and no damage observed. Ice from GUCP observed falling alongside the ET. Purge barrier material detaches and falls aft of the Orbiter.

E36 - Ice, from LO2 Feedline forward of ET-Orbiter attach bipod, falls between Orbiter and ET. No damage noted.

E40 - Typical debris observed falling aft of vehicle. Ice from LOX Feedline falling between ET and Orbiter noted. No impact with Orbiter observed and no damage noted.

E52 - Typical debris observed falling aft of vehicle. White area, probable frost, on ET nose cap louvers. Acoustic waves visible in clouds.

E54 - Pad debris noted rising and falling. Typical debris observed falling aft of vehicle. Typical ice/frost from 17-inch disconnects. Minimal free Hydrogen burning observed. Vapor from speed brake drain line on vertical stabilizer noted. The camera viewed the lower half of the vehicle and not the upper half as programmed.

E57 - Typical debris observed falling aft of vehicle.

E59 - Typical debris observed falling aft of vehicle.

E60 - Pad debris noted rising and falling.

E62 - Pad debris noted rising and falling. Typical debris observed falling aft of vehicle. Mach diamond formation in 3-2-1 order.

E63 - Pad debris noted rising and falling. Typical debris observed falling aft of vehicle. Typical ice/frost from 17-inch disconnects.

E204 - Vehicle partially obscured by clouds.

E205 - Glowing debris particles ejected from SRB plume prior to separation. Flow recirculation noted.

E207 - Typical debris observed falling aft of vehicle. Glowing debris particles ejected from SRB plume prior to, during and after separation. Debris-induced streaks in SSME plume. Linear optical distortions noted. Flow recirculation noted. Body flap motion noted.

E212 - Wisp of condensation collar briefly visible on forward section of SRBs.

E213 - Camera momentarily loses track of vehicle due to clouds. Wisp of condensation collar visible on left SRB.

E220 - Typical debris observed falling aft of vehicle. Debris-induced streaks in SSME plume. Processing marks noted on film. Camera momentarily loses track of vehicle in clouds.

E222 - Typical debris observed falling aft of vehicle. Glowing debris particles ejected from SRB plume after separation. Debris induced streaks in SSME plumes observed at: 18:41:15.163 UTC, 18:41:15.192 UTC, and 18:41:23.825 UTC.

E224 - Debris-induced streaks in SSME plume.

HH1 - Small details of ET TPS condition could not be resolved, however the general condition of the ET TPS appeared to be in good condition. The ET Thrust Panels appear to be in good condition. The SRB BSM burn scars appear nominal.

UMB3 - The EO-3 Bolt was observed protruding for the EO-3 fitting. TPS divots were observed near the bipod on the Intertank to LH2 Tank interface. The +Y Thrust Panel appeared to be in good condition.

FL101 - Typical flaking of TPS on aft ET/SRB attach. Upper ET/SRB attach strut momentarily twangs as SRB detaches from ET. Similar motion has been noted on other missions. Debris from ET/SRB attach strut area noted at separation. Film ends shortly after ET separation.

FL102 - Typical ablating of attach strut TPS. Long tape-like strand noted before and after separation. Motion of upper attach strut at separation observed. Protrusion of EO2 separation bolt was observed.

For further information concerning this report contact Tom Rieckhoff/TD53 at 256-544-7677 or Michael O'Farrell at 256-544-2620.

REPORT DOCUMENTATION PAGE

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14. ABSTRACT

A debris/ice/thermal protection system assessment and integrated photographic analysis was conducted for Shuttle mission STS-100. Debris inspections of the flight elements and launch pad were performed before and after launch. Icing conditions on the External Tank were assessed by the use of computer programs and infrared scanned data during cryogenic loading of the vehicle, followed by on-pad visual inspection. High speed photography of the launch was analyzed to identify ice/debris sources and evaluate potential vehicle damage and/or in-flight anomalies. The report documents the debris/ice/thermal protection system conditions and integrated photographic analysis of Space Shuttle mission STS-100 and the resulting effect of the Space Shuttle Program.

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